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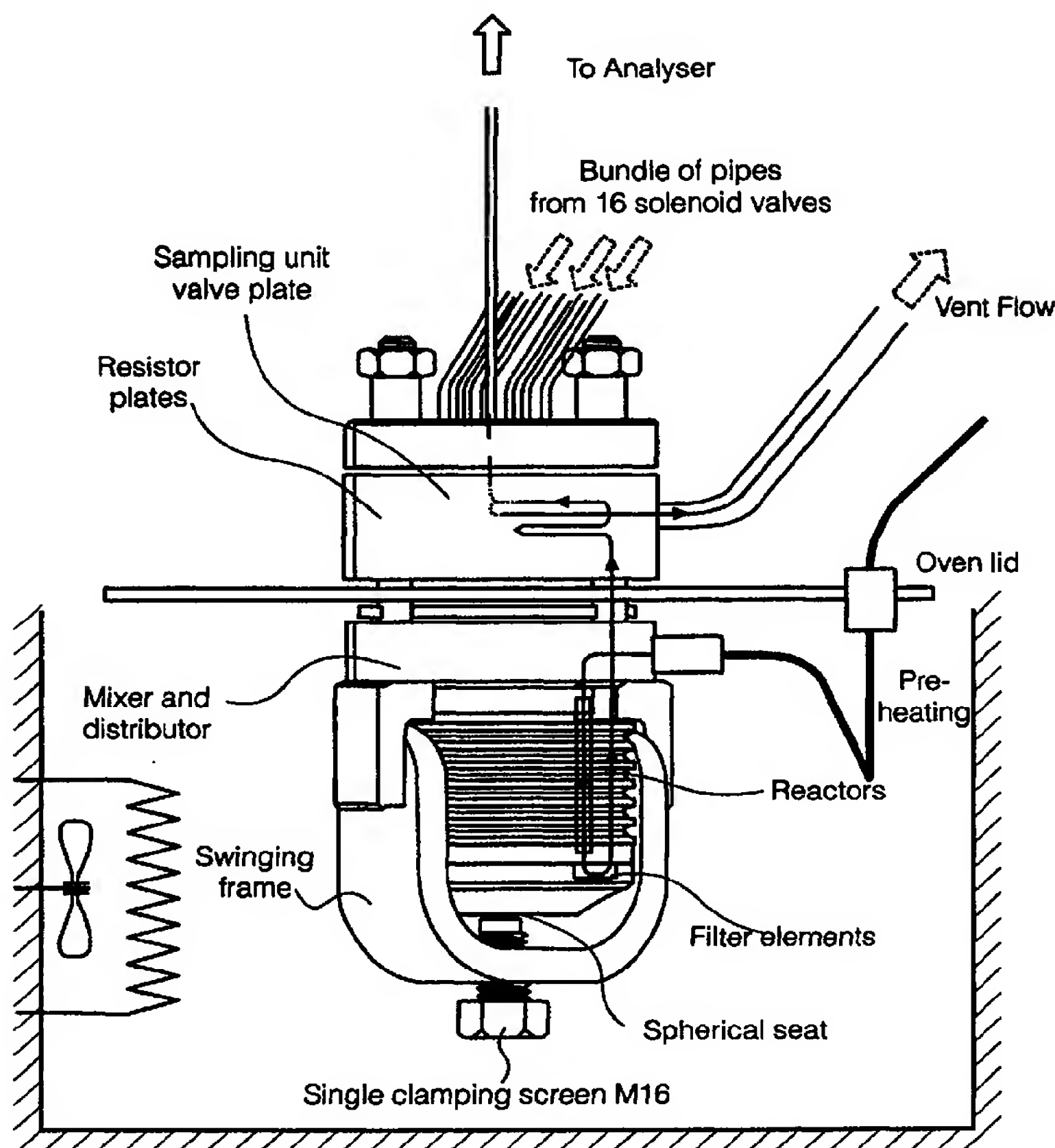
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(54) Title: MICROFLUIDICS



(57) Abstract: The present invention relates to microfluidics and in particular to a fluidic microreactor and constituent parts of such a microreactor. The production in a number of microreactors and the sampling of a number of fluids, that is, reactors products, is undertaken using a sampling unit or fluidic multiplexer that has no-moving parts, or fluidic multiplexer that has no-moving parts, or fluidic valves. The valves operate to allow the fluids to pass or block the fluids passage using control fluids that can form a barrier to the passage of that fluid. The fluids that are passed enter a common outlet channel for sampling by an analyser. Advantageously, a number of catalytic processes may be sampled using a single analyser.



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MICROFLUIDICS

The present invention relates to a microfluidics and to a microreactor and parts thereof.

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Modern chemical engineering has a tendency to use very small reactors, especially for exploratory and testing purposes. One of the advantages of the small size of the microreactors is the ability to control precisely the conditions under which the reaction takes place. This ability follows as a consequence of the effective and fast response of the microreactors to control actions. It is often possible to have a controller resident on the same chip as the microreactor. The typical parameters that can be controlled in such a microreactor include the temperature or pressure in the reactor and the product composition.

Within such a context, in particular for investigations of catalysis in microreactors, there is a need to control the flow of both reactants and reaction products to maintain the controlled parameters. Typically, microelectromechanical valves have been used for this task. Microdevices have been developed in which fluid flow is controlled by the action of moving components, such as, for example, miniature poppet valves.

Accordingly, a first aspect of the present invention provides a fluidic test assembly comprising a plurality of reactors for supplying reaction products to a common outlet channel via respective fluidic control valves, the valves being arranged to pass or prevent the flow of

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reaction products into the common outlet channel using respective control fluids that block or open the path of the reaction products to the common outlet channel.

5 Other aspects and embodiments are defined below and in the claims.

Embodiments of the present invention will now be described, by way of example only, with reference to the
10 accompanying drawings in which:

figure 1 illustrates schematically a microreactor test assembly;

figures 2a to 2c illustrate sectional and side views of embodiments of the test assembly;

15 figure 3 illustrates a perspective view of a microreactor body according to an embodiment; and

figures 4a and 4b illustrate a sectioned perspective views of embodiments of a microreactor body;

20 figure 5a to 5h illustrates embodiments of fluidic mixers for mixing two fluids;

figure 6 illustrates a carry-over ring for coupling reaction products from a microreactor to a pressure regulator;

25 figures 7a and 7b show plan and bottom perspective views of the carry-over ring;

figure 8 shows an embodiment of a sintered metal filter;

figure 9 shows an embodiment of a sieve ring;

30 figure 10 illustrates an embodiment of a bottom body;

figure 11 illustrates an embodiment of a fluidic multiplexer;

figure 12 illustrates an embodiment of a fluidic

valve for use in the multiplexer shown in figure 11;

figure 13 illustrates a further embodiment of a fluidic valve that can be used in the multiplexer shown in figure 11;

5 figure 14 illustrates a still further embodiment of a fluidic valve that can be used in the multiplexer shown in figure 11;

figure 15 illustrates an embodiment of a fluidic multiplexer that uses a fluidic valve as shown in figure
10 13;

figure 16 illustrates an embodiment of a multiplexer that uses fluidic valves as shown in figure 14;

figure 17 illustrates a further embodiment of a multiplexer that uses fluidic valves as shown in figure
15 14,

figure 18 shows a longitudinal section through a microreactor comprising a fluidic device according to an embodiment;

figure 19 shows schematically a microreactor in which flow control is realised by electrically generated thermal effects;

figure 20 illustrates a plurality of microreactors operating in parallel;

figure 21 shows a further plurality of microreactors
25 operating in parallel;

figure 22 shows the geometry of a fluidic valve according to a first embodiment of the present invention;

figure 23 shows the first embodiment of the present invention in a closed state;

30 figure 24 shows the fluidic valve of the first embodiment in an open state;

figure 25 shows a fluidic valve according to a second embodiment;

figure 26 shows a fluidic valve according to a third embodiment;

figure 27 shows a fluidic valve according to a fourth embodiment;

5 figure 28 illustrates a perspective view of the embodiment shown in figure 6;

figure 29 shows a fluidic valve according to a fifth embodiment of the present invention;

10 figure 30 shows a fluidic valve according to a sixth embodiment of the present invention;

figure 31 shows a fluidic sampling unit according to an embodiment of the present invention; and

figure 32 shows further embodiments of fluidic valves as a part of a fluidic multiplexer.

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The Multichannel Reactor Assembly

Referring to figure 1 there is shown a schematic diagram of an assembly for testing, for example, catalytic processes in several reactors that are operated in parallel. The test assembly 100 comprises first 102 and second 104 reactant supplies. In the embodiment shown, the first 102 and second 104 reactants are hydrogen and carbon monoxide. The rate of flow of the first 102 and second 104 reactants are controlled by respective valves 106 and 108.

The first 102 and second 104 reactants are supplied to a mixer 110 to ensure that they are thoroughly mixed. The mixer comprises no moving parts and is known as a fluidic mixer. The fluidic mixer 110 will be described hereafter in detail with reference to figures X to Y. Preferably, the output from the mixer 110 is fed to a

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distributor 112. The distributor 112 distributes substantially equal or other predetermined volumes of the mixed reactants to a number of microreactors 114. Each of the microreactors 114 contains beads manufactured from a neutral ceramic that have been coated with a very thin layer of a catalyst. Preferably, each microreactor contains a respective catalyst; the catalysts being a number of different catalysts that are under test. The outputs of the reactors are, optionally, fed indirectly via a pressure regulator 116 to an analyser. The pressure regulator 116 converts or changes the pressure of the reaction products from that pressure experienced within a respective microreactor to a pressure that is acceptable to, for example, an analyser (not shown).

15

The reaction product flows are fed into a sampling unit, or fluidic multiplexer, 118. The fluidic multiplexer 118 will be described in detail hereafter with reference to figures 11 to 17. The sampling unit does not contain any moving parts. The sampling unit is arranged to provide reaction product flow samples, selected from the reaction product flows produced by the microreactors 114, for output to a common outlet channel 120. The reaction product flows that are not currently being sampled are vented via a common vent 122.

25

Preferably, in an embodiment, the control fluids used in the fluidic valves of the fluidic multiplexer are flows of cold nitrogen 124.

30

Preferably, the control fluids are, in terms of Reynolds numbers, at least two orders of magnitude, that is, two decimal orders of magnitude, larger than those of

the reaction product flows. Advantageously, since the fluidic multiplexer 118 does not contain any moving parts, the sampling unit will not suffer from the usual mechanical fatigue and failure associated with sampling units that have mechanically actuatable valves.

Referring to figure 2a there is shown a longitudinal cross-section 200 of a catalysis test assembly according to an embodiment. The test assembly 200 comprises the first 102 and second 104 reactant supplies that are fed into the mixer 110, via two inlets 202 and 204. The mixer is, preferably, fluidic mixer 110 that is formed in an fluidic mixer plate described in detail hereafter with reference to figure 5a to 5f. The output from the fluidic mixer 110 is fed to a distribution manifold 112 via which the first 102 and second 104 reactants are fed into respective microreactor cavities such as, for example, the first 206 and second 208 reactors shown in figure 2. The reactor body which houses the reactor cavities is described in greater detail hereafter.

It can be seen that there are sintered metal sieves 210 and 212 that filter the first 102 and second 104 reactants prior to them entering the reactor cavities. The sintered metal filters 214 and 216 are disposed at the exit end of the reactor cavities 206 and 208. The sintered metal filters prevent clogging of the channels of the fluidic elements by solid particles that may become separated from the relatively fragile ceramic beads. The beads are relatively fragile as they are porous, which increases the surface area available to bear a catalyst coating.

The reaction products flow via conduits 218 and 220 to a pressure regulating device 222, such as, for example, resistor plates (which are described hereafter). The pressure regulator 224 is arranged to lower the pressure of the output 226 of the fluidic multiplexer 228, relative to the pressures within the respective reactors.

The fluidic multiplexer 228 is arranged to feed an output channel 226 that is common for all input channels to the fluidic multiplexer 228. The fluidic multiplexer 228 selects, using appropriately actuated fluidic valves, a flow of reaction product from all of the available flows of reaction products for output to the common outlet channel 226. The control fluids 124 for the fluidic valves, which are described hereafter in detail, are supplied to those valves via corresponding conduits 230. The test assembly 200 further comprises, within the pressure regulator, a vent plate 232 that is arranged to cool the reaction products.

It can be appreciated that the reactor is constructed from a hollow substantially cylindrical body which has a cylindrical cavity 234 therein. It can be seen that the axes 236 and 238 are not co-linear with the conduits 218 and 220. In a preferred embodiment, the axes 236 and 238 of the reactor cavities are disposed radially inward relative to the conduits 218 and 220. Reducing the outer diameter of the reactor body assists in improving the system dynamics such as providing an improved temperature system response.

It can be appreciated from figure 2 that the supply

pipes carrying the first 102 and second 104 reactants, the distribution manifold 112, and the reactors are all contained within a heated oven. The pressure regulator 224 and the fluidic multiplexer 228 are all housed on the exterior of the oven. By having relatively long conduits for supplying the first 102 and second 104 reactants, these conduits serve as means for pre-heating the reactants prior to those reactants being used in the catalysis processes under test.

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Referring to figure 2b, there is shown an alternative embodiment. It can be seen that the supply pipes carrying the first and second reactants 102 and 104 are arranged to feed the microcavities from the top rather than from the bottom as in figure 1. This has the advantage that the risk of beads contained within the cavities being lifted or displaced by the flow of reactants and reaction products through the cavities is removed or at least substantially reduced.

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The embodiment shown in figure 2b additionally comprises a swinging frame that supports a single M16 clamping screw. In contrast, the embodiment shown in figure 2a uses four M14 clamping screws. It can be appreciated that the component count and cost of the second embodiment shown in figure 2b are reduced relative to the first embodiment shown in figure 2a. All other aspects of the embodiment shown in figure 2b are identical in operation to the corresponding aspects of figure 2a.

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Figure 2c shows an enlarged perspective view of the reactor body and supporting swinging frame. It can be

seen that the second embodiment, when changing or replenishing the catalyst, only needs to break one seal, that is, the upper most seal shown in figure 2c. Once that seal has been broken, the reactor body can be
5 pivoted about an axis that is perpendicular to the axes of the reactor body to gain access to or empty the reactor cavities.

Referring to figure 3 there is shown a perspective
10 view of an embodiment of a reactor body 300. The reactor cavities 302 are circumferentially disposed relative to the central axis (not shown) of the reactor body. Each reactor cavity has a diameter of 6mm and a length of 60mm giving a volume of 28.3mm^3 . The reactor body comprises an
15 internal cavity 234 as discussed above in relation to figure 2a. The external surface 304 comprises a number of ribs, castalations, undulations or other means for increasing the external surface area of the reactor body. It will be appreciated that such ribs will assist in the
20 transfer of heat into or out of the reactor cavities 302.

Preferably, the reactor body is manufactured from stainless steel. It can be appreciated by ensuring, firstly, that the body is hollow, secondly that it has a
25 relatively small diameter and, thirdly, that the external surface bears ribs 304, the system response of the reactor body to a change in temperature is relatively rapid. This relatively rapid system response follows as a consequence of the relatively low mass and a relatively
30 high heat transfer surface of the reactor. The reactor body has a volume of $155,875\text{mm}^3$, which is significantly smaller than a rectangular equivalent body having dimensions of 99mm x 99mm x 60mm. The volume of such a

rectangular equivalent reactor body would be $587,608\text{mm}^3$.

A sealing contact surface 306 is provided at each end face of the reactor body 300 for sealing engagement with the distribution manifold 112 and the pressure regulator 224. It can be appreciated that the sealing surfaces are relatively small. In an embodiment, the area of the sealing surfaces is preferably 2337.3 mm^2 . In other embodiments that surface area may be different such as, for example, 3064mm^2 .

Referring to figure 4 there is shown a sectional view 400 of an embodiment of the reactor body 300. It can be appreciated that the reactor cavities 206 and 208 have a substantially constant cross-section. These cavities are formed by drilling sixteen 6mm diameter holes. The sixteen holes are disposed at a radius of 60mm from the central axis 402 of the reactor body. The length of the reactor is 60mm. The diameter of the internal cylindrical cavity 234 of the reactor body is 45mm. Chamfered shoulders 404, 406, 408 and 410 are arranged to form inwardly facing cylindrical surfaces 412 and 414. The surfaces 412 and 414 are precisely inclined to ensure a proper fit to the other components of the assembly.

It will be appreciated that precise machining is expensive. The increase in the diameter to 45mm on the inner most surface of the body means that such precise machining need not be performed over the whole of the inner surface and is restricted to those portions where it is needed.

The outer edges of the reactor body are also chamfered. Preferably, 1mm, 45° chamfers are provided. The diameter of the internal inwardly facing cylindrical surfaces 412 and 414 is 44mm.

5

The ribs on the external surface are formed via peaks and troughs. A trough has a radius of 1.8mm and a peak has a radius of 1mm. The points of inflexion between a trough and respective peaks either side of the
10 trough are arranged such that the tangents of two points of inflexion subtend an angle of 30°. The first trough, or minima, is located at a distance of 11mm from the closest sealing contact surface 306 thereto. The 6mm
15 diameter reactor cavities are uniformly distributed around a 60mm diameter circle.

Figure 4b shows a sectional view of the reactor body of the second embodiment. It can be seen from figure 2d that return channels are provided which carry reaction
20 products from the lower end of the reactor cavities to the upper end where those reaction products are fed into the fluidic multiplexer, optionally, via a pressure regulator. The diameters of the return channels in an
25 embodiment are preferably 2.6 mm. However, other embodiments are envisaged in which the diameter of the return channels are 3.5 mm in diameter. The reactor body also comprises a pressure equilibrium hole which allows the pressure within the central cylindrical reactor body
30 cavity to be in equilibrium with that of the exterior of the reactor body. The lower circular face of the reactor body comprises a recess for receiving the single M16 clamping screw. The cylindrical plate that engages the bottom of the reactor body comprises a number of recesses

for receiving corresponding sintered metal filters such as described hereafter with reference to figure 8. The filters form a filtered communication path between the microreactor cavities and the return channels.

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Referring to figures 5a to 5h there are shown embodiments of fluidic mixers for use in the text assemblies. The fluidic mixers will be described in greater detail hereafter.

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Referring to figure 6 there is shown a carry-over ring 600 with a quadrant thereof shown in cross section. The carry-over ring is arranged to allow the supply of reaction products from the reactor cavities to the pressure regulating device notwithstanding the absence of a co-linear relationship between the axes of the microreactors and the axes of the inlets of the pressure regulating device. The overall outer diameter of the carry-over ring is 80.2mm. The inner diameter of the carry-over ring 600 is 44mm H9. The carry-over ring comprises a number of cylindrical recesses 602 to 626 which are arranged, in use, to be concentric with the 6mm reactor cavities. The cylindrical recesses to 602 to 626, in use, house the sintered metal filters 216 and 214 as shown in figure 2a. The centre or axes of the cylindrical recesses are arranged on a 63.6mm diameter circle. The diameter of each recess is 9.6mm. The depth of each recess is 3mm. The overall depth of the carry-over ring 600 is 8mm. The carry-over ring 600 comprises shoulders 628 and 630 which bear an annular plateau 632 as can be seen from figure 7b. Each of the cylindrical recesses 602 to 626 has through-holes such as, for example, the through holes shown in section 634 and 636

30

and 638. The centres of the through holes 634 to 638 and all other through holes of the carry-over ring 600 are centred on a diameter of 70mm. The diameter of each through hole is 2.6mm. The height of the shoulders 628
5 and 630 is 1.5mm. Each shoulder 628 and 630 has a 1.6mm radius which leads up to the annular plateau 632. The inner diameter of the annular plateau 632 is 64mm. The outer diameter of the annular plateau is 76mm. The inner facing cylindrical surface 640 of the carry-over ring 600
10 bears a positioning groove 642 to allow correct azimuthal positioning of the cylindrical recesses 602 to 626 with respect to the corresponding microreactors.

It can be appreciated that the diameters of the
15 cylindrical recesses 602 to 626 are greater than the corresponding diameters of the microcavities. The internal shoulders formed as a consequence of the difference in diameters are arranged to allow the sintered metal filters to be supported by the sealing
20 contact surface 306. Such an arrangement prevents the sintered metal filters from becoming dislodged. The sintered metal filters 614 and 616 ensure that the 2.6mm diameter through-holes, such as, for example, through-holes 630, do not become blocked.

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Referring to figures 7a and 7b, there is shown both sides of the carry-over ring 600. Figure 7a shows the sealing contact surface facing side 702 of the carry-over ring 600. Figure 7b shows the pressure regulator facing
30 side 704 of the carry-over ring 600. Figure 7a shows more clearly the eccentric arrangement of the through-holes and the cylindrical recesses for the filters. Figure 7b shows more clearly the raised annular plateau

632.

Figure 8 illustrates schematically an embodiment of a sintered metal filter element 800. The sintered metal filter element 800 has a diameter of 9.6mm and a height of 3mm. Since the dimensions of the fluidic valves are of the order of 0.1mm, it can be appreciated that the correct operation of such valves can be impaired or prevented in the event of relatively large particles of material leaving any of the microreactors and finding their way into the fluidic valve. The sintered metal filter elements are designed to prevent the above.

Figure 9 illustrates an embodiment of a sieve ring 900. The sieve ring has an external diameter of 73mm and an internal diameter of 49mm. The thickness of the sieve ring 900 is 1mm. The sieve ring 900 may be manufactured from sintered metal. However, the flow of the first 102 and second 104 reactants through the sieve ring into the microreactors must be relatively unimpeded and without a significant change in pressure. The sieve ring 900 is disposed between the distribution manifold 112 and the lower sealing contact surface 306 of the reactor body. The sieve ring 900 is arranged to prevent egress of, for example, catalyst-coated beads from the microreactor cavities. It can be appreciated that the porosity of the sieve ring 900 will be much greater than the porosity of the filter elements 800.

Referring to figure 10, there is shown an embodiment of a bottom body 1000 which forms part of the distribution manifold and houses or provides a seat for the sieve ring 900. The bottom body comprises an annular

cavity 1002. The upper portion of the annular cavity 1002 has at each side thereof annular sieve ring seats 1004 and 1006 for supporting the annular sieve ring 900. The bottom body 1000 also comprises a reactor body positioning portion 1008 which is co-axial with the reactor body. The distribution manifold receives mixed reactants via first 1010 and second 1012 inlets. It can be seen from figure 10 that the distribution manifold is formed by the annular cavity of the bottom body 1000. The mass and weight of the bottom body 1000 is reduced significantly as a consequence of the reactor body positioning portion 1008 having a open, hollow, central cavity 1014. It can be appreciated that the reduced mass leads to improves in temperature response system dynamics and improve temperature control. Still further, the reduced mass provides for improved manual manipulation such as, for example, during the filling of the reactor cavities with beads.

20 The Fluidic Multiplexer

As indicated above, an aspect of the present invention relates to a fluidic multiplexer for sampling a number of fluid flows. The fluid flows may be taken from, for example, a number of chemical microreactors as described above.

One of the advantages of the small size of the microreactors is the ability to control precisely the process conditions under which the reaction takes place. This ability follows as a consequence of the effective and fast response of the microreactors to control actions. It is often possible to have a controller

resident on the same chip as the microreactor. The typical parameters that can be controlled in such a microreactor include the temperature or pressure in the reactor and the product composition.

5

A product composition analyser can be used to monitor the operation of a reactor. When operating or testing, for example, a catalytic process, a product composition analyser is typically connected to the output
10 of the microreactor. It can be appreciated that the analyser must be appropriate to or configured for the reaction product produced by the catalytic process under test. It is clearly not a cost effective option, in circumstances where more than one chemical reactor is
15 being monitored, to have one analyser per reactor. Whenever the variations in the processes are sufficiently slow, that is, the processes do not vary significantly during a sampling cycle, a single analyser may be used to monitor a number of reactors.

20

Ehrfeld W. (Ed) : "Microreaction Technology Industrial Prospects", Springer, Berlin 2000, ISBN 3-540-66964-7 discloses multiplexers that are suitable for taking fluid samples from mini-reactors and supplying
25 them to a product composition analyser. These known multiplexers operate using moving components. Therefore, they are large, that is, cannot be fabricated on a chip, require external mechanical drives, are prone to malfunctions, that is, breakage and/or seizure of the
30 moved or flexed parts, and are not suitable for high temperature applications.

Accordingly, an aspect of the present invention

provides a fluidic multiplexer for supplying to a common outlet channel one fluid selected from at least a first fluid channel and a second fluid channel each for carrying respective first and second fluid flows; the
5 multiplexer comprising a first fluidic valve to prevent to flow of the first fluid from the first fluid channel to the common outlet channel in response to flow of first control fluid from a first control inlet; and a second fluidic valve to prevent the flow of the second fluid
10 from the second fluid channel to the common outlet channel in response to flow of a second control fluid from a second control inlet.

Advantageously, the first and second fluids
15 represent, in a preferred embodiment, the reaction products of respective chemical reactors. These reaction products can be selectably directed to a common outlet channel under the control of the fluidic valves. The
output of the common outlet channel will be either the
20 first fluid or the second fluid according to whether the first or second fluidic valve has been actuated to prevent the flow of the first and second fluids respectively.

25 It can be appreciated that a single analyser can be used to sample reaction products of the two chemical processes occurring in the microreactors that are used to feed the first fluid channel and the second fluid channel respectively. Further, the use of a single analyser
30 finds particular application in chemical processes that vary slowly as compared to the time required for the analyser to cycle through all chemical processes.

Fluidic valves that operate by preventing or restricting the flow of a reaction product out of a corresponding supply nozzle may adversely affect the process conditions in a reactor by, for example, reducing
5 the flow rate of reactants or reaction product through the reactor or by varying the temperature or pressure in the reactor. It can be appreciated that such changes in a catalytic process can be disadvantageous.

10 Accordingly, an embodiment of the present invention provides a fluidic multiplexer in which the first fluidic valve comprises a first vent arranged to allow flow of the first fluid through the first vent in response to the first control fluid preventing the flow of the first
15 fluid to the common outlet channel.

A further embodiment of the present invention provides a fluidic multiplexer in which the second fluidic valve comprises a second vent arranged to allow
20 flow of the second fluid through the second vent in response to the second control fluid preventing the flow of the second fluid into the common outlet channel.

Advantageously, the fluid flow in the first and
25 second fluid channels can be arranged to be continuous even though the first and/or second fluidic valves has/have been actuated to prevent corresponding fluid flow to the common outlet channel. This ensures that the reactor conditions or chemical process conditions remain
30 substantially constant, that is, the flow rate, amongst other things, through a reactor may be maintained at a given value rather than there being a temporary cessation during sampling of another reaction product carried in.

another fluid channel.

A further embodiment of the present invention provides a fluidic multiplexer arranged to control
5 selectably the flow of first and second fluids into a common outlet channel using first and second fluidic valves, the first fluidic valve having a first inlet to supply the first fluid to a first outlet channel and a first control inlet to prevent flow of the first fluid to
10 the first outlet channel; the second fluidic valve having a second inlet to supply the second fluid to a second outlet channel and a second control inlet to prevent flow of the second fluid to the second outlet channel; the first and second outlet channels being arranged to feed
15 the common outlet channel.

Often the process conditions within a reactor and in relation to a reaction product are unsuitable for an analyser, which can be a relatively expensive and
20 delicate item of equipment. For example, the pressure of a reaction product may be incompatible with the operating conditions of an analyser.

Accordingly, an embodiment of the present invention
25 provides a fluidic multiplexer comprising a pressure regulator to establish, in use, a predeterminable pressure in the common outlet channel.

Advantageously, the predeterminable pressure can be
30 set to a pressure value that is acceptable to the analyser notwithstanding the pressures required by the chemical process under test.

A still further embodiment of the present invention provides a fluidic multiplexer further comprising a pressure regulator for changing the pressure of at least one of either the first and second fluids from respective
5 first and second pressures to a selectable pressure prior to feeding the common outlet channel.

A further advantage of the embodiments of the present invention is that fluid sampling can be
10 undertaken without using any moving components. Therefore, the fluid multiplexer is capable of operating under adverse conditions such as high temperature and/or in an aggressive fluid chemical environment under which corresponding electromechanical fluid valves would fail.

15

Still further the operation of the valve is not adversely effected by mechanical acceleration, and/or vibration.

20 Referring to figure 11 there is shown schematically a fluidic multiplexer 1100 for directing a plurality of fluids 1102 to 1110 to a common outlet channel 1112 using a plurality of fluidic valves 1114 to 1122 which can be selectively actuated to prevent or allow flow of a
25 corresponding one of the plurality of fluids 1102 to 1110.

Optionally, each channel for carrying the plurality of fluids 1102 to 1110 is interrupted by a gap which
30 forms a corresponding vent 1124 to 1132 that is arranged to maintain the fluid flow 1102 to 1110 of the plurality of fluids 1102 to 1110 even upon actuation of at least one of the fluidic valves 1114 to 1122. In the absence

of such vents, the fluid flows 1102 to 1110 would have to be terminated.

In the schematic embodiment shown in figure 11, there are only five inlets 1134 to 1142 for receiving, for example, corresponding reaction products, that is, the plurality of fluid flows 1102 to 1110. However it will be appreciated that the present invention is not limited thereto and, in practice, a significantly greater number of reaction product flows can be provided.

Each of the fluidic valves 1114 to 1122 is actuated by a corresponding flow of fluid, that is, a corresponding flow of control fluid 1144 to 1152. Each fluidic valve 1114 to 1122 comprises a respective control nozzle 1154 to 1162. The dimensions of each of the channels and control nozzles 1154 to 1162 are arranged, taking into account the velocities of the control fluids 1144 to 1152 and the reaction products 1102 to 1110 and the viscosities of the control fluids 1144 to 1152 and the reaction products 1102 to 1110, to result in extremely low respective Reynolds numbers such that the presence of a control fluid 1144 to 1152 in the path of a reaction product flow 1102 to 1110 can be, in some embodiments, sufficient to stop or at least reduce that reaction product flow 1102 to 1110. Preferably, the Reynolds numbers are less than 1100 and more preferably less than 40.

An embodiment is provided in which such a blocking effect is achieved by ensuring the viscosities of the control fluids 1144 to 1152 are greater than the viscosities of the reaction products 1102 to 1110.

Alternatively, the control fluids 1144 to 1152 and the reaction products 1102 to 1110 can be arranged to be mutually immiscible. Still further, an embodiment is provided in which the control fluid is a liquid and the
5 reaction product is a gas. In such a situation the control fluid is strongly held in position by the action of surface tension and viscous forces.

It can be appreciated from figure 11 that the fourth
10 fluid flow 1108 is the fluid that is coupled to the common outlet channel 1112 while the remaining reaction product flows 1102, 1104, 1106 and 1110 are vented via the corresponding vents 1124, 1126, 1128 and 1132 to a common vent 1164 in response to actuation of fluidic
15 valves 1114, 1116, 1118 and 1122. Accordingly, only the reaction product of the fourth channel is coupled to the common outlet channel for sampling by an analyser.

Referring to figure 12, there is shown, according to
20 an embodiment, a fluidic valve 1200 for controlling the flow of reaction product 1102 to the common outlet channel 1112. It can be appreciated from figure 12 that the fluidic valve 1200 is shown in a closed state. The embodiment shown in figure 12 can be manufactured by
25 etching substantially planar material to an appropriate depth. It can be appreciated from figure 12 that since the fluidic valve 1200 is in a closed state the reaction product 1102 will continue to flow via the channels 1202 and 1204 that form part of the vent rather than flowing
30 into the outlet channel.

The action of the control fluid in preventing the flow of the reaction product 1102 shown in figure 12 can

be accomplished by ensuring the control fluid 1114 is a very viscous liquid and, preferably, immiscible with fluids to be sampled, that is, the reaction product flows. If the above conditions are satisfied, only a
5 small amount of control fluid needs to be introduced into the path of a reaction product flow. However, if the control fluid and the reaction products are miscible and the control fluid cannot be expected to be held in or to maintain a stationary position by the action of viscosity
10 or under surface tension, it will be appreciated that some of the control fluid may be carried into the common outlet channel 1112. It will also be appreciated that, under such circumstances, the flow of some of the control fluid into the common outlet channel 1112 may also take
15 place during initial closure of the fluidic valve 1114. During the initial stages, that is, during partial closure of the fluidic valve 1200, a small amount of the control fluid emerging from a corresponding nozzle into the relatively strong full flow of the reaction product
20 1102 will result in a small amount of that control fluid being carried into the common outlet channel 1112. It is only after delivery of a sufficient volume of control fluid 1148 into the path of the reaction product 1102 that the fluidic valve will close and prevent the flow of
25 the reaction product 1102 into the common outlet channel.

While, under some circumstances, the flow of the control fluid into the common outlet channel may be acceptable, under other circumstances such flow may not
30 be acceptable. Therefore, an embodiment is provided in which the control fluid is selected so that an analyser connected to the common outlet channel 1112 does not generate a corresponding signal in response to the

presence of such a control fluid.

Still further, under certain circumstances, the flow of the control fluid into the analyser may represent a relatively large volume of the sample taken by the analyser and accordingly decrease, by way of dilution of the sample, the effectiveness of the analysis, that is, the analyser will have a product concentration threshold below which a reaction product cannot be reliably analysed. Therefore, an embodiment provides a fluidic valve 1114 in which the flow of control fluid is arranged to have a greater component opposing the direction of flow of the reaction product as compared to the component in the direction of flow of the reaction product. Referring to figure 13 there is shown an embodiment of a fluidic valve for achieving this aim. The embodiment shown in figure 13 provides a first channel 1302 for carrying a reaction product 1102. The first channel comprises a first nozzle 1304 for directing the reaction product 1102 towards a first outlet 1306 that is arranged to feed a common outlet channel 1112 via a pair of symmetrically shaped conduits 1308 and 1310. There is also provided a control nozzle 1154 that is arranged to produce a flow of control fluid 1312 which opposes the flow of reaction product through the first outlet channel 1306. It can be appreciated that under certain circumstances the control fluid may extend into a vented cavity 1124. The control nozzle is contained within the first outlet channel that leads the common outlet channel in the embodiment shown. This arrangement reduces the extent of any backflow 1314 of control fluid into the outlet channel during valve actuation or operation.

It can be appreciated that the embodiment shown in figure 13 may be manufactured by CVD and etching as appropriate.

5 Referring to figure 14 there is shown a further embodiment of a fluidic valve 1400 for achieving a more effective suppression of flow of the control fluid into the first outlet channel 1402. It can be appreciated that the direction of flow of the reaction product and
10 the control fluid are mutually opposite, and the control nozzle is inclined relative to the first outlet channel. The first outlet channel 1402, as with the above embodiments, is arranged to feed the common outlet channel 1112. The embodiment shown in figure 14 has the
15 advantage that there does not result an island of etched material, such as island 1316 shown in figure 13, which would lead to manufacturing complications if the valve structures from which the valves are constructed were deposited on a suitable substrate after etching rather
20 than prior to or during etching. It can be appreciated from figure 14 that at relatively high Reynolds numbers such as, for example, 1200, the jet or relatively fast flowing stream of control fluid would prevent the formation of a flow of the control fluid into the common
25 outlet and, preferably, generate a suction effect which would draw the fluid contained within the first outlet channel 1402 in a direction which opposes the flow of supply fluid towards the common outlet channel 1112.

30 Referring to figure 15 it can be seen there is disclosed a parallel arrangement of first and second channels 1502 and 1504 for carrying respective reaction products. The first and second channel 1502 and 1504 are

directed towards respective outlet channels 1506 and 1508 that are arranged to feed a common outlet channel 1510. The control nozzles 1512 and 1514 are arranged to direct respective control fluids such that they oppose the flow of reaction products flowing via the first and second inlet nozzles 1516 and 1518. It can be appreciated that the first and second inlet nozzles are substantially wider than the corresponding inlets 1520 and 1522 of the outlet channels and the control nozzles 1512 and 1514. There is also provided, in the embodiment shown in figure 15, a common vent 1524.

Referring to figure 16 there is shown an embodiment of the present invention in which each of a number of fluidic valves 1602 to 1608 controls the flow of a respective reaction product 1610 to 1616 using respective control fluids 1618 to 1624 fed via control fluid nozzles 1626 to 1632. The embodiment is arranged to control the flow of reaction products 1610 to 1616 into corresponding outlet channels 1634 to 1640. It can be seen from figure 16 that pairs of outlet channels of the fluidic valves, that is, outlet channels 1634 and 1636 and outlet channels 1638 and 1640, merge into first 1642 and second 1644 common outlet channels. The first 1642 and second 1644 common outlet channels also merge to form an overall common outlet channel 1646. The merging pairs of outlet channels have the advantage that they at least reduce or prevent the loss of a fluid sample currently under investigation via backflow into the channel of a fluid that is not current under investigation. The same applies to corresponding features of figure 17.

It can be seen from figure 16 that each fluidic

valve 1602 to 1608 has a vent 1648 to 1654. Each vent 1648 to 1654 has a corresponding opening 1656 to 1662 which is formed in an overlaying, vertically disposed, plate or larger having respective holes 1656 to 1662
5 etched therein.

It can be appreciated that an alternative embodiment to that shown in figure 16 is one in which, rather than having separate respective vents 1648 to 1654, at least
10 two of the vents can be combined into a common vent. A still further embodiment is envisaged in which all of the vents 1640 to 1654 are combined into a single vent as shown in figure 17 at 1700.

15 Models tested in the laboratory used Syngas™ as a supply fluid at a temperature of 400°C and a viscosity of $50 \times 10^{-6} \text{ m}^2/\text{s}$. The velocity of the supply fluid at the nozzle exit was 5 m/s. The laboratory models had the following dimensions: supply nozzle width 0.34 mm,
20 control nozzle width 0.24 mm and the nozzle depths were 0.15 mm. The gap between the supply nozzle exit and the output channel entrance was 1.14 mm. However, it will be appreciated in actual microfluidic applications, the dimensions will be smaller. Typically, the dimensions
25 may be three to five times smaller.

It can be appreciated that, due to the very low Reynolds numbers used in some or all of the embodiments of the present invention, the mere presence of a blockage
30 or control fluid can be sufficient to close a valve since, in those embodiments, no use of fluid inertia is made to close the valve as in the prior art. The extremely low Reynolds numbers are such that the inertial

effects are quickly damped or countered by fluid viscosity. Typically, the Reynolds numbers of the fluid flows of the embodiments of the present invention will be less than 100 and in some instances can be less than 40.

5

Embodiments of the present invention utilise a 0.34 mm nozzle width. Each valve occupies about a 5 mm x 5mm area. A complete fluidic multiplexer occupies a 80 mm x 15 mm area. The depths of the channels of the above
10 embodiments are 0.1016 mm.

It can be seen that the above embodiments have been described within a catalysis context, that is, within the context of controlling the flow of reaction products.
15 However, it will be appreciated that the present invention is not limited thereto. Embodiments can be realised in which the fluids flows that are controlled are fluids other than reaction products.

20 The magnitudes of the fluid flows of conventional fluidic valves are such that the supply fluid flow is significantly greater than the control fluid flow. However, the embodiments of the present can equally well use fluid flow magnitudes in which the control fluid flow
25 is at least equal to or significantly greater than the supply fluid flow. In some embodiments the control fluid flow may be at least 10 times greater than the supply fluid flow.

30 In applications such as, for example, high throughput catalysis testing, the range of volumes flows for the above embodiments may be between 10 cubic centimetres per minute and 30 cubic centimetres per

minute, which corresponds to $60 \cdot 10^{-6}$ kg/s to $180 \cdot 10^{-6}$ kg/s. The above volume flow rate limits were imposed, in practical realisations, by the operating parameters of the infrared analyser used to undertake the testing and
 5 do not reflect any hydrodynamic limitations of the above embodiments. It will be appreciated that the hydrodynamic limitations are determined from the Reynolds number, Re, by

$$10 \quad \dot{M}[\text{kg/s}] = \frac{\text{Re} \cdot h \cdot \nu}{\nu}$$

where ν = fluid viscosity
 ν = fluid specific volume; and
 h = the cavity depths in metres.

15 At one end of the spectrum, the skilled man could envisage the flow of a gas at $\nu = 10 \cdot 10^{-6}$ m²/s, $\nu = 0.5$ m³/kg at an Re = 1 in a microchannel for which the nozzle depth is 5µm, which give a value of $\dot{M} = 100 \cdot 10^{-2}$ kg/s. However, it will be appreciated that the other end of the spectrum
 20 may have the following prevailing conditions $\nu = 10 \cdot 10^{-6}$ m²/s, $\nu = 10 \cdot 10^{-3}$ m³/kg at an Re = 1000 in a microchannel for which the nozzle depth is 2mm, which give a value of $\dot{M} = 20 \cdot 10^{-3}$ kg/s.

25 Furthermore, in the above embodiments it is envisaged that the control flow could be between 0.1 and 5 times that of the supply flow.

The Fluidic Mixer

30

An aspect of the present invention relates to

devices for mixing fluids and, in particular, to microfluidic mixers for use in the above described assembly.

5 A well known problem in microchemistry is the efficient mixing of reactants. Such efficient mixing is crucial for almost all synthesis reactions. It is also essential in analytical chemistry where the results often strongly depend on the concentration of the reagents. It
10 will be appreciated that classical mechanical stirrers do not provide a practical solution to the requirement for efficient and thorough mixing when the scale of the device of the mixing devices and the microreactors involved are of the order of several microns in size. A
15 proposed solution which overcomes the difficulties associated with mechanical stirrers (which have a limited operating life and suffer from mechanical fatigue) are so called "static mixers". These static mixers generate small-sized volumes of fluid and bring them into mutual
20 contact. A mixed formation is achieved by relying upon diffusive transport between the volumes. The fluids to be mixed are brought into contact in a longitudinal flow within a channel having a length determined by the rate of diffusion of the fluids to be mixed. To use
25 effectively available space, channel lengths should be small which requires small sizes of volumes generated in the mixer.

Conventionally, high diffusion rates may be achieved
30 in a turbulent flow regime in which the fluids to be mixed have associated Reynolds numbers that are relatively large so that turbulent mixing can occur. However, such a turbulent flow regime is generally not

available in microdevices with fluid flows having relatively low Reynolds numbers.

Accordingly, an aspect of the present invention
5 provides a fluidic mixer comprising a first nozzle and a second nozzle to feed a cavity having at least two exit channels; the first and second nozzles being arranged to produce mutually opposing first and second fluid flows that form in at least one exit channel interleaved layers
10 of the first fluid and the second fluid.

Advantageously, embodiments of the present invention allow static fluidic mixers to be realised. In particular, embodiments can be realised to mix fluid
15 flows at relatively low Reynolds numbers.

A second aspect of the present invention provides a mixer comprising a first nozzle and a second nozzle that feed a cavity having at least two exit channels; the
20 first and second nozzles being arranged to produce mutually opposing flows of a first fluid and a second fluid that are arranged to oscillate to feed in an alternating manner the two exit channels.

Referring to figure 5a there is shown a microfluidic
25 mixer 5a100 comprising a first inlet 5a102 for a first fluid and a second inlet 5a104 for a second fluid. The first inlet 5a102 has a first nozzle 5a106. The second inlet 5a104 has a corresponding second nozzle 5a108.
30 Both the first nozzle 5a106 and the second nozzle 5a108 are directed towards an interaction cavity 5a110, that is, the nozzles are arranged to produce mutually opposing fluid flows, or at least fluid flows having mutually

opposing components. The mixer 5a100 also comprises first 5a112 and second 5a114 exit channels. The axes of the first 5a112 and the second 5a114 exit channels are perpendicular to the axes of the first 5a106 and second 5a108 nozzles. It can be appreciated from figure 5a that the microfluidic mixer has been etched from a body 5a116. In some embodiments, the inlet was 2.94 times the nozzle width, b. However, it has been found that the behaviour of the nozzles is relatively insensitive to changes in inlet width providing there is a contraction of the cross-sectional area of the inlet as compared to the cross-sectional area of the nozzle which is of the order of a factor of two.

Referring to figure 5b there is shown the embodiment of a microfluidic mixer 5a100 as shown in figure 5a together with relative dimensions of the features of the microfluidic mixer. It can be seen that the inlets 5a102 and 5a104 have parallel walls 5b202 to 5b208 which are connected at the ends most remote from the respective nozzles 5a106 and 5a108 by semicircular surfaces 5b210 and 5b212. The parallel walls 5b202 to 5b208 are coupled with respective constriction portions 5b214 to 5b220 which narrow the inlets 5a102 and 5a104 to form respective nozzle channels 5b222 and 5b224 of the first 5a106 and second 5a108 nozzles.

Preferably, the constriction portions are formed as inflexions between first 5b226 and second 5b228 radii. The inflexion portions reduce the width of the inlets to the width of the channel of the nozzles. The constriction portions comprise, in an embodiment, respective linear portions between two different radii. The inflexions that

form the constriction portions are defined by a convex (or inwardly turning) radius and a concave (or outwardly turning) radius preferably with a tangential linear portion therebetween. An inwardly turning radius is a
5 radius which turns towards a respective nozzle axis and an outwardly turning radius is a radius which turns away from a respective nozzle axis.

Each nozzle has a nozzle exit formed by respective
10 nozzle lips 5b230 and 5b232. The nozzle exits (and nozzle lips 5b230 and 5b232) are separated by a pre-determined distance, s. It can be appreciated that the nozzle lips protrude into the volume defined by the side
walls 5b234 to 5b240 of the exit channels 5a112 and
15 5a114.

The nozzle lips comprise respective linear portions between two radii of pre-determinable values. The
nozzles have respective axes (only the axis 5b242 of the
20 first nozzle 5a106 is shown in figure 5b). Preferably, the axes of the first 5a106 and second 5a104 nozzles are colinear. It can be appreciated from figures 5a and 5b that the linear portions of the constriction and the
nozzle lips are substantially parallel and are inclined
25 at a pre-determined angle relative to a respective nozzle axis. A preferred embodiment preferably has angles of inclination of 45° . However, it will be appreciated that other angles may be used which provide a sufficient
contraction down to a preferred nozzle width. For
30 example, the angles may take a value in the range of 20° to 60° .

In a preferred embodiment the nozzle width is b.

The dimensions of the remaining features of the microfluidic mixer are defined relative to the nozzle width b . Preferably, b has submillimetre dimensions. However, the value of b will in practice be determined by the operating conditions for the mixer. Embodiments can be realised in which the value of b has a lower limit of 0.005 mm. Embodiments can be realised in which the value of b has an upper limit of 10 mm.

The inwardly turning radii of the constriction portions have radii $r_1 = 2.9b$. Preferably, the outwardly turning radii have radii of $r_2 = 2.3b$. The inflexions which form the lips of the nozzle have an inwardly turning radius of $r_3 = 3.5b$ and an outwardly turning radius of $r_4 = 0.3b$. The linear portions of the nozzle lips have a length of $l_1 = 1.04b$. The separation, s , between the nozzle exits, that is, the inner most parts of the nozzle lips, is $s=3b$. The widths of the first 5a112 and second 5a114 exit channels are $m=6.7b$. The lengths of the channels of the nozzles 5a106 and 5a108 are $l_2 = 1.4b$. The widths of the first 5a102 and second 5a104 inlets are $l_3=2.94b$. Preferably, the aspect ratio of the device, that is, the aspect ratio of the nozzle channels as defined by $\lambda=\frac{h}{b}$ where h is the depth of the etched features of the micro fluidic mixer. Preferably, $h = 0.44b$.

Although the above relative dimensions may be preferred, it will be appreciated that embodiments can be realised which deviate from the above preferred dimensions. There are, for some embodiments, preferred ranges of relative dimensions. Table 1 below illustrates

preferred ranges of the dimensions which may be realised jointly or severally in any combination to achieve oscillation or mixing within embodiments of a microfluidic mixer.

5

Parameter name	Parameter symbol	lower multiplier	upper multiplier
Inlet channel width	l_3	2	10
First inflexion linear portion	l_1	1	5
second inflexion linear portion	l_2	1	5
First inflexion linear portion inclination angle	α_1	20	60
second inflexion linear portion inclination angle	α_2	20	60

Table 1

A practical, but relatively large scale, embodiment

of the present invention was realised. The embodiment was operated using water. The fluid flow from the first nozzle comprised clear water. The fluid flow from the second nozzle comprised coloured water. The value of b for the practical embodiment was b=3.4mm. Table 2 shows various operating parameters associated with the practical embodiment. Indeed, table 2 illustrates two sets of operating conditions. The operating conditions are labelled G and H.

10

Parameter	G	H
Re	410	415
u	1.1	1.81
Sh	0.041	0.022
Sk	16.8	9.1

Table 2

where the Reynolds number, $Re = \frac{bw}{\nu}$

15 Strouhal number $Sh = \frac{fb}{w}$, and

Stokes number $Sk = Re \cdot Sh = \frac{fb^2}{\nu}$

where b = the nozzle width,

20 w is the fluid nozzle exit velocity;

f is the frequency of oscillation.

Referring to figure 5c there is shown a schematic
 25 illustration of a static mixer 300 which comprises first

5c302 and second 5c304 inlets that carry respective fluids 5c306 and 5c308. The fluids leave the inlets via nozzle exits 5c310 and 5c312. It can be seen that the first fluid 5c306 produces a flow which oscillates
5 between two positions 5c314 and 5c316. The second fluid also produces a flow which oscillates between two positions. However, only one position 5c318 of the second flow is shown. A first exit channel carries the mixed first 5c306 and second 5c308 fluids. The nozzle
10 exit velocities are both assumed to be w . It can be seen that the first 5c306 and second 5c308 fluids are initially carried in interleaved layers of thickness δ and at a velocity of w_p . The interleaved layers 5c322 result from the oscillation of the first 5c306 and second
15 5c308 fluids emanating from their respective nozzles. It will be appreciated that figure 5c is highly schematic. In practice the interleaved fluid layers are not linear, they assume a complex curved shape.

20 Referring to figure 5d there is shown a still photograph 5d400 taken from a video recording of the above practical realisation of a static mixer. The still clearly shows first 5d102 and second 5d104 inlets which feed the first 5d106 and second 5d108 nozzles. The fluid
25 flow 5d402 emanating from the first nozzle 5d106 can be seen to form a feedback loop which influences the flow of the first nozzle. It has been observed that the fluid flow 5d402 is deflected to reach a substantially fully deflected position as shown in figure 5d. It is thought
30 that the fluid flow 5d402 when it finally arrives at the fully deflected position as shown in figure 5d, cannot remain deflected and switches to the other exit channel. The fluid flow 5d402 is forced to straighten and after

doing so performs a further traversal motion which results in the fluid flow being deflected into the other exit channel. It is thought that the overswing to the other exit channel is caused by fluid inertia. It is also thought that the feedback action of the leading front of the feedback loop may cause the fluid flow 5d402 to be deflected when that front acts on the fluid flow 5d402 as it emanates from the nozzle 5d106. An embodiment provides for the feedback loop of given nozzle to influence the flow of fluid from that nozzle substantially at the exit of that nozzle. The feedback loops alternate, that is, oscillate about the respective axes of the nozzles.

Referring to figure 5e there is shown, without wishing to be bound by any theory, a current mathematical model of the oscillation of embodiments of the fluidic mixers. The model is used to estimate the length the feedback loop of a fluid flow, such a fluid flow 5d402 of figure 5d. It can be seen that the expression for the feedback loop path length has been expressed in terms of the width of the interaction cavity, s , and the width of the exit channels, m . It can be seen that the approximate path length is given

$$\text{path length} = 2s + \left(\frac{m-s}{2} \right) = m+s = m (1+\sigma) \text{ where } \sigma = \frac{s}{m}$$

It will be appreciated that the simplified expression for the feedback loop path length does not consider transverse motion or transverse components of the feedback loop path. It can also be appreciated that the assumption is made that the fluid flow 5d402 reaches the opposing wall of the exit channel which, as can be

observed from figure 5d, it does not. Therefore, the simplified mathematical model shown in figure 5e has been adjusted to incorporate a dimensionless parameter, μ , which can be varied to allow the predicted oscillation frequency to match the experimentally determined oscillation frequency. Therefore, the corrected fluid flow path length is $m(\mu+\sigma)$ where μ is of the order of 1 and involves corrections for effects including the fluid velocity not being constant for the whole of the feedback loop path and the period not being equal to twice the fluid flow traversal time.

It can be appreciated for the simplified mathematical model shown in figure 5e that the oscillation period is equal to twice the fluid flow traversal time. Therefore $\Delta t_p = \frac{2b}{\beta w} (1+\sigma)$ which equates to (two path lengths nozzle exit velocity), the frequency, f , is given by $f = \frac{1}{\Delta t_p} = \frac{\beta w}{2b(1+\sigma)}$ and the Strouhal number $Sh = \frac{fb}{w} = \frac{\beta}{2(1+\sigma)}$. The corrected expressions taking into account the value of μ are:

$$\text{oscillation period } \Delta t_p = \frac{2b}{\beta w} (\mu + \sigma)$$

$$\text{frequency } f = \frac{1}{\Delta t_p} = \frac{\beta w}{2b(\mu + \sigma)}; \text{ and}$$

$$\text{Strouhal number} = \frac{fb}{w} = \frac{\beta}{2(\mu + \sigma)}$$

Table 3 below shows the experimental data derived from the above practical embodiment for the operating conditions shown in column G of table 2 above.

Experimental Data	
Parameter	Value
w	0.118 m/s
f	1.618 Hz
Sh	0.0466
Sk	17

Table 3

5 The frequency of oscillation of 1.618 Hz compares
favourably with the theoretically predicted frequency of
1.783 Hz. It can be seen that there is an error of about
10% between the measured frequency and the predicted
frequency. The predicted frequency may be made to match
10 the experimental frequency if the corrected expressions
are used with a value of $\mu = 1.1489$.

It will be appreciated that the frequency of
oscillation varies according to required mixer
15 operational parameters. Embodiments can be realised in
which the predetermined frequency of oscillation has a
value in the range of 0.2 Hz to 100 kHz.

Also the Strouhal number can also be made to vary.
20 Embodiments are envisaged in which the Strouhal number
takes a value in the range $0.01 \leq Sh \leq 0.4$. Preferably,
an embodiment is envisaged in which $Sh = 0.04$.

The process of producing interleaved layers of fluid
25 5c322 as shown in figure 5c can, without wishing to be
bound by any particular theory, be modelled as follows.
The time taken to form one layer is approximately equal

to one half of the oscillation period Δt_p . During that time the flow in the exit channels travels a distance given by

$$w_p \Delta t_p / 2.$$

This gives rise to a layer thickness

$$\delta = w_p \frac{b}{\beta w} (\mu + \sigma).$$

Due to the continuity condition, $w_p = bw/m$, the thickness of the generated layer, relative to the nozzle exit width, is $\frac{\delta}{b} = \mu + \sigma$. Inserting the above values leads to a theoretical prediction of $\frac{\delta}{b} = 1.6$, which compares very favourably with the actual value determined from experiment G of $\frac{\delta}{b} = 1.53$.

It will be appreciated that the parameters governing the interleaved layer thickness δ are balanced to achieve within a required length of the exit channel, mixing by diffusive transport of the first 5c306 and second 5c308 fluids.

As mentioned above, it can be very desirable in certain situations to ensure that efficient mixing of reactants is achieved for synthesis reactions. Furthermore, in analytical chemistry, when the results often strongly depend on the concentration of the reagents, thorough mixing is even more desirable. Therefore, an embodiment of the invention provides a plurality of static mixers such as shown in figure 5f.

Figure 5f shows a two stage mixer 5f600 which mixes first 5f602 and second 5f604 fluids. The two stage mixer 5f600 comprises two primary mixers 5f606 that are arranged to feed a secondary mixer 5f608. At least one
5 or both of the primary and secondary mixers may be realised using any or a combination of the above embodiments. It can be seen that the exit channels 5f610, 5f612 and 5f614 of the primary mixers 5f606 are arranged to feed or coincide with the inlets for the
10 nozzles 5f616 and 5f618 of the secondary mixer 5f608. The mixed fluid contained in the exit channels 5f620 and 5f622 of the secondary mixer 5f608 can then be output for further processing.

15 In a preferred embodiment, the two stage mixer 5f600 comprises a number of separate channels 5f624. The separate channels 5f624 are fed from the exit channels 5f602 and 5f622 of the secondary mixer 5f608.

20 Although the embodiment shown in figure 5f uses first and second fluid to feed both of the primary mixers, it will be appreciated that the present invention is not limited thereto. Embodiments can be realised in which the two primary mixers are used to different
25 fluids. The mixed different fluids would then, in turn, be mixed within the secondary mixer.

Preferably, the above embodiments are operated at Reynolds numbers which are of the order of less than 450,
30 and preferably of the order of 10 to 100.

In a preferred embodiment the plurality of channels 5f624 are arranged to feed respective microreactors for

high throughout catalyst testing.

It will be appreciated that the above embodiments are substantially planar. A cover or top plates
5 containing through holes is arranged to cover the etched features. The through holes are arranged to coincide with the inlet and outlets of the mixer.

A number of stills take from a video recording of
10 the operation of the practical embodiment of the mixer are shown in figures 5g to 5h. In figure 5g, a first fluid 5g00 has been deflected to one side of the nozzle axes while the second fluid 5g02 has been deflected to the other side of the nozzle axes. Accordingly, in the
15 still of figure 5g00, the first fluid feeds the flow 5g04 of the upper outlet channel and the second fluid feeds the flow 5g06 of the lower outlet channel. Referring to figure 5h, it can be appreciated that the position is the reverse of that shown in figure 5ga. The first fluid
20 5g00 has been deflected downwards to feed the flow 5g06 carried by the lower outlet channel. The second fluid 5g02 has been deflected upwards to feed the flow 5g04 carried by the upper outlet channel.

25 It will be appreciated that embodiments of the present invention are arranged to mix substantially different fluids having differing viscosities, flow rates etc. Therefore, each nozzle would be arranged to accommodate a respective fluid. The embodiments
30 described above are substantially symmetrical. However, embodiments can be realised that are asymmetrical, which may result from mixing different fluids. In such asymmetrical embodiments the nozzle widths would be

calculated for a respective fluid. If the fluids were different, the respective nozzle widths would be different.

5 It has been observed that the aspect ratio of the nozzle influences the degree and/or frequency of oscillation. Preferably, the above embodiments are provided such that the aspect ratio is greater than one. However, the above embodiments, in some applications, may
10 find an aspect ratio of one or less to be acceptable.

Although the above embodiments have been described with reference to a preferred value of $l_2 = 1.4b$, the present invention is not limited to that value. The
15 above embodiments can be varied such that l_2 has a value given by $0.5b \leq l_2 \leq 10b$.

The Fluidic Valves

20 An aspect of the present invention relates to fluidic flow rate control and to a fluidic device and particularly to use of the same in an assembly as described above.

25 Present day chemical engineering has a tendency to perform chemical reactions in a fluid (ie gas and/or liquid) phase in sub-millimetre sized microreactors. Typically, a large number of such microreactors are arranged to operate in parallel and are formed in a
30 common metal plate or, for low temperature applications, a box or plate manufactured from other materials such as plastics. An advantage of the small size of the microreactors is the capability of controlling very

precisely the chemical reaction. Due to the small volume of reactants in relation to the relatively large heat or mass transfer surface, a fast control or system response is possible. The parameters that are controlled in such
5 microreactors include temperature and/or pressure in the reactor and, particularly, the fluid flow rate of the fluid or fluids passing through the reactor.

In large reactors the fluid is controlled by
10 mechanically operated valves. The valves are typically arranged to restrict the fluid flow rate at the reactor exit to maintain a pre-determined or required pressure level inside the reactor.

15 It is in principle also possible to use such mechanical valves for flow rate control in microreactors. However, the use of such mechanical valves is problematical. This is particularly the case if the chemical reaction in the reactor is exothermic so that
20 the generated products are at an elevated temperature. This leads to extreme difficulty in the design and operation in the micro-size valves based on the use of moving components. If the micro-size valves are supported by elastic members, such as springs formed (eg
25 by etching), from the common plate in which the reactor cavities are made, the moving components have a severely limited useful life. The limited useful life follows as a consequence of the elastic members being highly stressed to achieve relatively long motion.
30 Alternatively, the moving components of such a micro-sized valve may be constructed from freely moveable components that are unsupported. This leads to assembly difficulties and there is a danger of the valves becoming

stuck.

The above problems are further compounded by the fact that many electro-mechanical phenomena, such as piezoelectric effect or magnetostrictive effect, which are used for generating the required mechanical motion in such a micro-sized valve, usually cease above a certain temperature.

Conventionally, the above problems may be, at least in part, addressed by substituting the mechanical valves by fluidic flow rate control valves. Fluidic devices do not have mechanically moveable components. The absence of such moveable components in fluidic devices, which are based upon aerodynamic or hydrodynamic phenomena in fixed geometry cavities, makes these devices relatively simple to manufacture. Furthermore, such fluidic devices have a significant service life. The risk of a moving component becoming seized or breaking is removed.

A typical fluidic device that is used for restricting fluid flow in a large-scale reactor is the vortex amplifier. Unfortunately, the use of such a vortex amplifier is limited to situations which result in or require relatively high values of Reynolds numbers. At low Reynolds numbers, the vortex amplifiers, as well as other known fluidic devices, do not work effectively or do not work at all. Typically, vortex amplifiers do not operate well at Reynolds numbers of below $Re = 1000$. For good performance, a vortex amplifier should be operated with a Reynolds number of at least $Re = 10,000$. It is well known that in Wormley's experiments, the vortex amplifiers stopped working completely at $Re = 750$.

Accordingly, an aspect of the present invention provides a fluidic control device for controlling the flow rate of a controlled fluid using a control fluid, the device comprising an outlet chamber having mutually facing inlet nozzles that are arranged to form mutually opposing streams of control fluid and controlled fluid to control the rate of flow of the controlled fluid.

In microreactors using fluidic devices according to the present invention, the operating Reynolds numbers tend to be very small due to the small overall dimensions, small fluid flows (dictated by the requirements of the reactant residence time in the reactor) and the often high fluid viscosities (especially if the fluid is a gas at a high temperature).

A further aspect of the present invention provides a reactor or microreactor comprising at least one inlet arranged to feed a first reactant to or into an entrance end of a reaction chamber; the reaction chamber having an exit end comprising a fluidic control device as claimed in any proceeding claim for controlling the flow rate of fluid through the reaction chamber.

A still further aspect of the present invention provides a method for controlling the rate of flow of a controlled fluid using a control fluid, the method comprising the steps of forming the controlled fluid and the control fluid into mutually facing streams of fluid injected into a fixed geometry chamber.

Referring to figure 18, there is shown a

microreactor 1820 in longitudinal section. The chemical reaction takes place in a cavity that is made by etching a thin basic plate 1801 of stainless steel. The basic plate 1801 is covered by a similar flat cover plate (not shown) to form a closed reactor cavity. The rate at which fluid flows through the microreactor (that is, the reactor flow rate) is controlled by a fluidic device. The flow through the reactor cavity is from left to right.

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The microreactor 1820 shown in figure 18 is an example of a catalytic reactor. Inside the reactor cavity there are, for example, packed beads 1821 having a catalyst coated on their surface. Grids are formed at the entrance to and exit from the microreactor cavity to prevent the loss of the packed beads 1821. At the entrance to the reactor cavity there is an inlet grid 1822a. The inlet grid 1822a comprises a row of projections. The projections can be made during an etching process by arranging for several islands of stainless steel to remain after etching. Between the islands of stainless steel are channels which are too narrow for the packed beads 1821 to pass through. Similarly, an outlet grid 1822b is situated at the exit end of the reactor cavity. The outlet grid 1822b prevents any of the packed beads from escaping downstream from the reactor cavity.

Two inlets, that is, a first reactant inlet 1806a and a second reactant inlet 1806b, are provided to allow the supply of a reactant fluid or reactant fluids into the reactor cavity. The reactant fluids enter the cavity where they mix and, together with contact with the

catalyst, undergo a required reaction.

At the exit end of the reactor cavity is a fluidic device comprising outlet chamber 1809 that is connected
5 to a product outlet 1807 through which the products of the reaction are output.

The fluidic device comprises mutually facing reactor 1802 and control 1803 nozzles. The reactor nozzle 1802
10 is formed by appropriate shaping of the exit of the microreactor 1820. In a preferred embodiment, the appropriate shape of the reactor nozzle 1802 is that of a planar sub-sonic nozzle comprising an upstream contraction part of converging or progressively reducing
15 cross-section and a constant cross-section exit channel. The constant cross-section exit channel opens into the outlet chamber 1809. The reactor nozzle 1802 is preferably coaxial with the control nozzle 1803. The control nozzle 1803 has the same or a substantially
20 similar planar sub-sonic shape with an upstream contraction part of converging or progressively reducing cross-section and a constant cross section exit channel. The exit channel of the control nozzle 1803 opens into the outlet chamber 1809. The control nozzle is arranged
25 to receive a control fluid from a control fluid source 1804 and an actuator 1843 is used to control the flow rate of the control fluid.

It will be appreciated that the nozzles do not need
30 to be coaxial. It is sufficient is the nozzles are arranged such that a the flow of the control fluid interferes with or obstructs the flow of the controlled fluid.

The fluidic device is used, in the embodiment shown, to maintain pre-determined operating conditions within the reactor. Preferably, the operating conditions can be
5 sensed by appropriately positioned and selected sensors 1811. The signals from the sensors are fed, via a feedback line 1810, to a controller 1842 which controls the actuation of the actuator 1843.

10 The operation of the fluidic device is based upon jet collision. The control fluid leaves the control nozzle 1803 as a jet that is directed to oppose the jet of the reaction products, that is, the controlled fluid, leaving the reactor nozzle 1802. The jets from the
15 reactor nozzle 1802 and the control nozzle 1803 have opposing velocities. The respective jets meet in the gap 1805. The velocities of the respective jets from the reactor nozzles 1802 and control nozzle 1803 decrease towards the zero value at a stagnation point. The flow
20 rates of the controlled and control fluids are arranged to result in relatively low respective Reynolds numbers. Preferably, the Reynolds numbers are less than or equal to 40 and preferably less than or equal to ten. In an embodiment the Reynolds number is arranged to be
25 substantially 9. The Reynolds number, Re , for a fluid is calculated by $Re = \text{nozzle width} \times \text{nozzle exit velocity} / \text{fluid viscosity}$, where nozzle width is the width of the nozzle measured in the plane of the basic plate, the nozzle exit velocity is the velocity of the fluid
30 leaving the nozzle and the fluid viscosity is the viscosity of the fluid leaving the nozzle.

At such low Reynolds numbers, the relatively large

viscous damping of fluid motion ensures that the position of the stagnation point remains substantially fixed. The location of the stagnation point depends upon the relative magnitudes of the flow rates of the control and control fluids. Generally, if the velocity of the control fluid is increased relative to that of the controlled fluid, the stagnation point moves towards the reactor nozzle 1802. If the velocity of the control fluid relative to that of the controlled fluid decreases, the stagnation point moves towards the control nozzle 1803. The stagnation point may be positioned, under particular circumstances or under particular operating conditions, so that the flow rate of reactants through the microreactor 1820 is decreased and the residence time in the reactor cavity is increased. In effect, the cross-section through which the reactor products can leave the reactor is varied according to the flow rate of the control fluid. The above described mechanism of varying the available cross-section through which the reaction products in or of the controlled fluid can flow, has been found to be effective even at extremely low Reynolds numbers, that is at Reynolds numbers which are equal to or less than 10, where standard methods of fluidic control are not applicable or effective.

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Referring to figure 19, there is shown a further microreactor having a fluidic device according to an embodiment of the present invention. It can be appreciated that the geometry of the basic part of the reactor 1920 with its two inlets for reactants 1906a and 1906b is the same as for figure 18. Again, the microreactor of figure 19 also comprises a similar inlet grid 1922a and a similar outlet grid 1922b. A reactor

heater, in the form of conductive foils, is arranged to maintain, upon connection to a current source 1915, the temperature of the reactor cavity at a predetermined level. The predetermined level is selected according to the reaction to be performed. It can be appreciated that electric heating of a fluid is an effective method of controlling fluid flow rate in a low Reynolds number regime inside a microchannel. Such a flow is characterised by very large hydraulic losses due to the strong influence of viscosity. Since viscosity depends upon temperature, that is, it increases with temperature in gasses and decreases with temperature in liquids, similar Ohmic heating by electric current in a conductive material exposed to the fluid flow leads to a change in hydraulic losses and therefore a change in flow rate. However, it will be appreciated that the same heating element cannot be used to achieve concurrently the two different purposes. On the one hand, heating is required to maintain a particular temperature level inside the reactor cavity for proper kinetics of the chemical reaction. In contrast, the changes in heating to achieve variation of fluid flow rate due to thermal changes in viscosity cannot be, in the prior art, implemented simultaneously in the same microreactor channel.

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Accordingly, an embodiment provides, as shown in figure 19, a second reactant tap in the second reactant inlet 1906b. Although the tap 1912 is taken from the second reactant inlet 1906b, it can be appreciated that the tap could equally well be taken from the first reactant inlet 1906a. The second reactant tap 1912 leads to the actuator 1943, which takes the form of a reactor heater that is substantially similar to reactor heater

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1913. The reactor heater 1943 comprises conductive foils on the walls of a control chamber 1939 connected to a current controller 1942 via first 19431 and second 19432 terminals. Changes in viscosity of the control fluid are realised by heating the control fluid contained within the control chamber 1939. This change in viscosity leads, in turn, to a change in the flow rate of the control fluid. As described above, a change in the flow rate of the control fluid leads to a change in the flow rate of the reactants through the microreactor, that is, to a change in the flow rate of the controlled fluid.

Referring to figure 20, there is shown a plurality of microreactors that operate in parallel. The flow rate of each microreactor 2020 can be controlled independently by the controller 2042. The control fluid may be supplied by, for example, a pressurised cylinder of control fluid serving as a control fluid source 2004.

It can be seen that the microreactors 2020, in this embodiment, have substantially the same configuration as the microreactor shown in figure 18. The microreactors are of a planar design, manufactured by etching and packed with catalyst beads. It can be appreciated that the three microreactors shown in figure 20 may form part of a larger number of parallel microreactors. The same structural features in the microreactors as shown in figure 20 will not be described in detail in relation to corresponding feature of figure 18. However, it will be appreciated that the same structures having the same reference numeral perform substantially the same function. It can be appreciated from figure 20 that a single reactant inlet 2006 is provided rather than the

first 2006a and second 2006b reactant inlets shown in figure 17. The single reactant inlet 2006 can be used to carry pre-mixed reactants to the reactor cavity. At the exit of each reactor cavity there is a fluidic control device according to an embodiment of the present invention. The fluidic device comprises a reactor nozzle 2002 formed by shaping the ends of the microreactors 2020 into a constriction or contraction followed by a constant cross-section exit channels which open into the corresponding outlet chambers 2009. Disposed opposite to and coaxial with the reactor nozzles 2002 are control nozzles 2003. The reactor nozzles 2002 and control nozzles 2003 are separated by a predetermined distance. Preferably, the predetermined distance is a multiple of the nozzle width. Still more preferably, the predetermined distance is substantially 2.7 times a corresponding nozzle width. The rate of flow of control fluid into each control nozzle 2003 is adjusted by a respective one of the actuators 2043 in response to a respective control signal from the controller 2042. Although not shown in figure 20, it can be appreciated that the actuators 2043 may be substantially similar to the actuator 2043 shown and described in relation to figure 18. The microreactor cavities and outlet chambers 2009 are covered by a cover plate (not shown). The cover plate comprises openings, preferably oval openings, which are positioned to provide an exit for the fluids contained within outlet chambers 2009. The oval openings are arranged to feed an outlet channel 2020. The outlet channel directs the fluid contained therein into a separator 2008 which separates the control fluid from the controlled fluid, that is, the reactor products are separated by separator 2008 from the control fluid. It

can be appreciated that the oval openings allow fluid flow from the outlet chamber 2009 in a direction that is substantially normal to the plane containing the reactor cavity and/or the outlet chamber.

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Referring to figure 21, there is shown the three microreactors 2120. The microreactors 2120 operate parallel and may form part of a larger number of microreactors. The microreactors 2120 in the embodiment shown in figure 21 have or can have substantially the same configuration as those shown in figures 18, 19 and 20. Again, the cavities have a planar design and are realised by etching. The cavities of the microreactors are packed with catalyst beads.

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It can be appreciated that the reactors are heated by the heat generated by the reaction. A separate means of electrically heating the microreactors 2120 is not provided. However, it will be appreciated that separate means of heating the microreactors can be provided substantially as shown in figure 19. Similarly, means for heating the control fluid, and thereby controlling velocity, can also be provided.

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In the embodiment shown in figure 21, the flow rate in each of the microreactors is again controlled independently by actuators 2143 in response to control signals output from controller 2142.

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It can be seen that the exit ends of the microreactors 2120 are provided with respective fluidic devices according to an embodiment of the present invention. There is provided an inlet grid 2122a and an

outlet grid 2122b in each reactor cavity for keeping the catalyst beads within the reactor cavities.

The flow rate in each of the microreactors 2120 is again controlled independently in response to signals from the controller 2142. However, in this embodiment, it can be appreciated that the outlet channel 2119 comprises a product tap 2114 via which the reactor product fluid can also be used as a control fluid. In effect, an amount of the reaction product is removed from the main flow of reaction product within the outlet channel 2119 via product tap 2114 and fed back to the control nozzles 2103 as a control fluid. It can be appreciated that this embodiment removes the need for a fluid separator 2108. Preferably, there is also provided a pump 2115 that is used for controlling or establishing the pressure of the control fluid. The control fluid available at product tap 2114 is at a lower pressure than the pressure required at the control nozzle 2103. Therefore, the pump can be arranged to increase the pressure of the control fluid.

Furthermore, there is also, preferably, provided a heat exchanger 2116 for controlling the temperature of the control fluid. The heat exchanger 2116 is used, in this embodiment, to lower the temperature of the control fluid by removing the heat generated during the exothermic reactions in the microreactors 2120.

Preferably, the heat exchanger 2116 is disposed between the product tap 2114 and the pump 2115.

In the embodiment shown in figure 21, it can be seen

that the two reactants fed into the microreactors are not pre-mixed but are kept separate until a short time before they enter the microreactors 2120 where they do not need intensive mixing. It can be seen that the separate
5 inlets, the first reactant inlets 2106a and the second reactant inlet 2106b, are, in this embodiment, arranged in substantially the same manner as the separate product outlets 2107, that is the oval openings, as described in relation to figure 20.

10

It can be appreciated that the oval openings at the entrance and exit ends of the microcavities allow fluid flow in a direction that is substantially normal to the plane containing the microreactor cavities. At the
15 entrance end of the microreactors, the oval openings form the first reactant inlet 2106a. At the exit end of the microreactors, the oval openings 2107 allow reactant product 2137 to escape from the outlet chamber 2109 into the outlet channel.

20

It can be seen that the control nozzles 2103 also open into the outlet chambers 2109 such that the streams of the controlled and control fluids are mutually opposing. As described earlier, the flow rate of the
25 control fluid is controlled by actuators 2143 in response to control signals from controller 2142. The actuators 2143 in this and in the other embodiments may be mechanically actuable valves such as, for example, solenoid valves. It can be appreciated that these
30 mechanically actuable valves can be disposed sufficiently remotely from the control nozzles 2113 so as not to be affected adversely by the exothermic reactions occurring in the microreactors 2120.

The present invention can be used to stop completely the flow of controlled fluid.

5 The depth of the etching of the basic plate for the above embodiments can be set at any predetermined depth which can still allow a relatively low Reynolds number to be realised. In the above embodiments, the depth of all cavities, including the nozzles and outlet chambers, was
10 0.44 nozzle widths.

 The outlet chambers 2109 in the above embodiments preferably have an increasing width with transverse distance from the axis of the two inlet nozzles.
15 Preferably, the width of the outlet chamber is ten nozzle widths. The width of the oval openings also corresponds to ten nozzle widths.

 Although the above embodiments have been described
20 in relation to catalytic reactors, the present invention is not limited thereto. Other types of reactors could equally well be realised.

 Although the above embodiment utilise control and
25 reactor nozzles that have comparable dimensions, the present invention is not limited thereto. Embodiments can be realised in which the reactor and control nozzles have different dimensions. An embodiment has been realised in which the control nozzle was smaller than the
30 reactor nozzle. In particular, the a control nozzle having a width of 70.6% of the width of the reactor nozzle still operates effectively.

It will be appreciated that a "subsonic nozzle" is characterised by a decreasing cross section in the direction of fluid flow. A planar nozzle is characterised by a rectangular cross section which includes a square cross-section.

However, it will be appreciated that the above described valves which use opposing nozzles cannot produce a backflow effect. Accordingly, an aspect of the present invention provides fluidic valves and, more particularly, to micro-fluidic valves for use in controlling the flow of a fluid.

Within a micro device context there is often a need to control fluid flow. In the particular case of microreactors, there is a need to control the flow of both reactants and reaction products. Typically, microelectromechanical valves have been used to control the flow of such reactants and reaction products. Micro-devices have been developed in which fluid flow is controlled by the action of moving components, such as, for example, miniature poppet valves. However, the moveable components are typically supported by elastic members, such as springs formed by etching. Accordingly, the lifetime of the valve is dependent upon the mechanical lifetime of the elastic members supporting the moving components. To obtain a given flow rate or mass flow rate, it may be necessary to have a relatively long stroke for the moving components. Such a relatively long stroke results in the elastic members being highly stressed. The repeated stressing of the elastic members leads to mechanical fatigue and ultimately to failure of the valve.

To overcome some of the problems of the above mechanical valves, such as failure due to mechanical fatigue, fluidic valves have been developed. Typically, the operation of such fluidic valves is based upon the hydrodynamic effects of flowing fluids in a fixed geometry environment. Fluidic valves of this type are disclosed, for example, in "*Valvole fluidiche senza parti mobili*", *Oleodinamica-pneumatica rivista delle applicazioni fluidodinamiche e controllo dei sistemi*, Numero 3 - marzo 1998, anno 39, v216, ISSN 1 122 - 5017. In the valves disclosed in the above paper, the action of the electromechanically moveable parts is replaced by the dynamic effects of accelerated fluids. However, it can be appreciated that most hydrodynamic principles used in such large-scale fluidic valves are suitable only for operation at relatively high Reynolds numbers. The valves typically operate in a turbulent flow regime in contrast to the typically laminar flows of microdevices. However, in microdevices, with their typical laminar flow characteristic, it is not possible to use the designs of standard, large scale, fluidic valves as, at low Reynolds numbers, the inertial action, damped by viscous forces, is not sufficiently effective.

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Accordingly, a further aspect of the present invention provides a fluidic valve comprising first and second nozzles, having respective first and second axes, arranged to produce a first flow of fluid and a second flow of fluid, the first flow of fluid being arranged to flow from the first nozzle to an outlet channel having an outlet axis; the second flow of fluid being arranged to prevent the flow of the first flow of fluid to the outlet

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channel.

Advantageously, the present invention enables the fluidic valve to be closed to prevent flow of a supply
5 fluid, a first fluid, into the outlet channel and ultimately through the valve. Still further, the embodiments of the valves can be used in the above described assembly.

10 An embodiment provides a fluidic valve in which the first axis, second axis and outlet axis are coplanar.

If the supply nozzle and the control nozzle are colinear and mutually opposing, upon actuation of the
15 valve, that is, upon supply of the control fluid to close the valve, the control fluid can interfere with the flow of the reactor product or supply fluid and adversely affect the flow of reactants through a corresponding microreactor, for example. Therefore, an embodiment of
20 the present invention provides a fluidic valve in which the second fluid flow is arranged such that the second fluid flow does not flow into the first nozzle or supply nozzle. Preferably, the orientation of the first and second axis are such that the second fluid flow does not
25 flow into the first nozzle.

A further embodiment provides a fluidic valve in which at least two of the first axis, second axis and outlet axis are not colinear.

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However, in such valves, there exists the problem of the control or barrier fluid flowing into or forming part of the outlet fluid. In effect, the barrier fluid or

control fluid flows downstream and passes out of the outlet channel. In some instances, such as when an analyser is connected to the outlet channel, the presence of the control fluid may dilute the fluid to be analysed to a level below the appropriate operating threshold of the analyser.

A still further problem associated with mutually opposing first and second, or supply and control, flows, is the inability of the control flow to influence the flow of fluid in an outlet channel. Accordingly, an embodiment provides a fluidic valve in which the flow of the second fluid is arranged to prevent the flow of the fluid in the outlet channel in a first predetermined direction. Preferably, an embodiment of the present invention provides a fluidic valve in which the flow of the second fluid is arranged to induce or influence the flow of fluid in the outlet channel in a second predetermined direction. The first and second predetermined directions are preferably mutually opposite. In effect, a back flow of flow in the outlet channel is induced by flow of the control fluid.

A preferred embodiment provides a fluidic valve in which the mutual positions and orientation of the second nozzle and the outlet channel are arranged to induce flow of fluid in the outlet channel in response to flow of the second fluid flow.

Preferably, the angle subtended by the second axis and the outlet axis is acute. It will be appreciated that the value of the angle used in any realisation represents a balance between two conflicting

requirements. Firstly, the angle that is very effective for moving and preventing the first fluid from reaching the outlet is substantially 90° . Secondly, an angle that is very effective for generating outlet flow in the second direction is a very acute angle. It can be appreciated that as the acute angle tends to zero the entrainment effect of one fluid flow upon another fluid increases. Therefore, the optimum angle of an embodiment depends upon the application.

An embodiment is provided in which the angle subtended by the first axis and the second axis is at least obtuse.

In an embodiment there is provided a fluidic valve in which the projection of the cross-section of the control nozzle onto a plane normal to the second axis does not intersect with the projection of the cross-section of the first or supply nozzle onto the plane normal to the second axis.

It can be appreciated that one of the aspects of the present invention is to preserve the flow of the supply fluid even during actuation of the valve. Accordingly, an aspect of the present invention provides a fluidic valve comprising a vent arranged to allow flow of the first fluid through the vent in response to the control fluid flow preventing or reducing the flow of the first fluid to the outlet channel.

A further aspect of the present invention provides a method for controlling the flow of an outlet fluid stream fed from an inlet fluid flow, the method comprising the

steps of arranging for a control fluid flow to intersect the inlet fluid flow to prevent the inlet fluid flow feeding the outlet fluid flow thereby preventing the flow of the outlet fluid.

5

Embodiments of the present invention will now be described, by way of example only, with reference to figures 22 to 32:

10 Referring to figure 22 there is shown a first embodiment of a fluidic valve 2200 according to the present invention. The fluidic valve 2200 comprises a first, or supply, nozzle 2202 for supplying a first, or supply fluid 2204 to an outlet channel 106. The supply
15 nozzle 2202 has, in part, a constant cross-section 2208 and a first axis 2210. The outlet channel 2206 also has a constant cross-section part 2212 and an outlet channel axis 2214. The exit of the supply nozzle 2202 comprises first 2216 and second 2218 supply nozzle lips. The inlet
20 2220 of the outlet channel 2206 comprises first 2222 and second 2224 outlet channel inlet lips.

Figure 22 also shows a control nozzle 2226 for supplying a second, or control, fluid 2228 in such a
25 manner as to prevent the communication of supply fluid 2204 to the outlet channel 2206 and, more particularly, to prevent the supply fluid 2204 entering the outlet channel 2206 via the inlet 2220.

30 It can be appreciated that the control nozzle comprises first 2230 and second 2232 control nozzle lips. In the embodiment shown in figure 22, it can be seen that the second inlet channel lip 2224 coincides with the

second control nozzle lip 2232, that is, the second inlet lip of the outlet channel 2206 is also the second control nozzle lip 2232.

5 The control nozzle also comprises a respective axis 2234. It can be seen that the directions of flow of the supply fluid 2204, the control fluid 2228 and the flow of fluid in the outer channel 2206 are along the respective axes 2210, 2214 and 2234 of the supply nozzle, the outlet
10 channel 2206 and the control nozzle 2226. All three of the axes 2210, 2214 and 2234 intersect at a common point, that is, at a point of intersection 2236. It can be seen that all three axes 2210, 2214 and 2234, while being coplanar, are not colinear. The angle subtended by the
15 first axis 2210 and the control axis 2234, that is, the control inclination angle, α , measured in the clockwise direction from the first axis 2210 to the control nozzle, is acute. The value of the angle α will depend upon the particular application. For example in some applications
20 α may have a value of 25° , depending upon the size of the first lip 2216. In practical embodiments, the control inclination angle, α , may take values in the range of 25° to 120° . A suitable control inclination angle, α , is 30° for situations that require reverse flow in the outlet
25 channel. However, it will be appreciated that angles of inclination other than 30° can be utilised according to particular design requirements.

It can be appreciated that the control angle, α , is
30 selected, in light of the nozzle dimensions, viscosities of fluids and velocities of fluids, to at least, upon flow of the control fluid past the inlet 2220 of the outlet channel 2206, prevent flow of the supply fluid

2204 into the outlet channel 2206. Preferably, the control inclination angle, α , in conjunction with the viscosities and velocities of the fluids involved and the dimensions of the nozzles and outlet channel, is arranged to prevent flow of fluid in the outlet channel in a first, or outward flow, direction. The flow of the control fluid in a preferred embodiment, is arranged to induce flow of the fluid in the outlet channel in a second direction which opposes the first direction. In effect, the flow of control fluid induces a back-flow of the fluid contained within the outlet channel.

In a preferred embodiment, the flow of the control fluid is arranged to produce vortices in the vicinity of the inlet 2220 of the outlet channel 2206. These vortices induce the back-flow of fluid in the outlet channel 2206.

It can be seen that the first axis 2210 of the supply nozzle 102 and the outlet axis 2214 of the outlet channel 2206 subtend an angle, β , known as the outlet channel inclination angle. The outlet channel inclination angle is measured anticlockwise from the first axis 2210. The outlet channel inclination angle, β , may have a value taken from the range of -30° to 30° to avoid a change of flow direction at the outlet channel entrance and the associated hydraulic loss for high Reynolds numbers, that is, $Re > 2200$. However, if the flow in the outlet channel is generated by pressure action, that is, at Re substantially 1 or less, large values of β can be used since at small velocities the hydraulic loss associated with changing flow direction ceases to be of importance.

An embodiment is provided in which the cross-sectional area of the outlet channel 2206 is smaller than the cross sectional area of the supply nozzle 2202.

5

It can be seen that a continuation line 2238 of a wall of the control nozzle does not project into the opening of the supply nozzle 2202. Preferably, the continuation line 2238 projects in such a manner that it does not intersect the lips of the supply nozzle 2202. In effect, the projection of the cross-section of the control nozzle 2226 onto a plane (not shown) that is normal to the control nozzle axis 2234 does not intersect the normal projection of the cross section of the supply nozzle 2202 onto that plane.

10
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In the embodiment shown in figure 22 the control nozzle outlet defined by the first 2230 and second 2232 control nozzle lips is formed in a side wall of the outlet channel 2206, that is, the control nozzle outlet is downstream from the inlet 2220 of the outlet channel 2206 defined by the outlet channel first 2222 and second 2224 nozzle lips.

20

Referring to figure 23, there is shown the embodiment of a fluidic valve 2200 as described above with reference to figure 22 in a closed state. It can be seen that the control fluid 2228 forms a barrier 2202 across in the inlet 2220 of the outlet channel 2206. The barrier 2202 prevents the supply fluid 2204 from feeding or entering the outlet channel 2206. Preferably, the flow of supply fluid 2204 from the supply nozzle 2202 is not impeded by the presence of the barrier 2202 created

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by the control fluid 2228. This arrangement has the advantage that, in a catalysis environment, the supply fluid 2204 received from, for example, a microreactor (not shown) flows at a constant rate. In effect, the
5 flow rate of reactants through such a microreactor and the generation of the supply fluid 2210, that is, the reaction product, is not impeded, such that constant reactor conditions are maintained.

10 The barrier 2302 created by the control fluid 2228 may be arranged, in circumstances where it is required merely to prevent the supply fluid 2204 entering the outlet channel 2206, to operate at very low supply fluid Reynolds numbers such as, for example, 40 or less.
15 However, in circumstances where there is a requirement for a back-flow to be induced by the flow of the control fluid, higher control fluid Reynolds numbers would be required. At higher control fluid Reynolds number, vortices are generated by the flow of the control fluid
20 2228 in the vicinity of an entrainment interface 2304. It can be appreciated that since the vortices are generated in the vicinity of the entrainment interface, fluid is drawn from the outlet channel 2206 and carried into the vent 2306 or, at least, towards the vent 2306.
25 Since, in the embodiment shown in figure 23, the control nozzle is located inside the outlet channel 2206 by a predeterminable distance, m , the entrainment effect of the control fluid 2228 acts upon the fluid contained within the outlet channel 2206. In some embodiments, at
30 low Reynolds numbers, the mere presence of a substantially static barrier of control fluid would be sufficient to prevent flow of the supply fluid into the outlet channel.

Referring to figure 24 there is shown the fluidic valve 2200 of figure 22 in an open state. In the open state the supply fluid 2204 flows from the supply nozzle 2202 into the outlet channel 2206 in the absence of a control fluid 2228. In the embodiment shown, it can be appreciated that the cross-sectional areas of the supply nozzle outlet and the inlet of the outlet channel are different. An advantage of ensuring that the cross-sectional area of the outlet channel 2206 is smaller than the cross sectional area of the supply nozzle 2202 is that a higher percentage or proportion of the fluid contained within the outlet channel 2206 is derived from the supply fluid 2210 rather than being a mix of the supply fluid 2210 and the surrounding fluid 2402 (which would typically be spent control nozzle fluid).

If the cross-sectional area of the outlet channel 106 is less than a cross-sectional area of the supply nozzle 102, such an arrangement invariably involves the sacrifice of supply fluid 2204 as can be seen from the two arms of supply fluid 2404 and 2406 which propagate along the vertical wall contained within the plane 2236 of the fluidic valve 2200. The sacrificed fluid 2404 and 2406 is, preferably, carried away via a vent (not shown). It will be appreciated that such sacrifice of the supply fluid 2204 can be used to ensure or improve the purity of the sampled fluid, that is, of the fluid flowing in the outlet channel. However, others embodiments may not tolerate such a sacrifice of fluid flow. Therefore, embodiments can be realised in which the sacrifice fluid is at least reduced or eliminated at the expense of the purity of the fluid contained within the outlet channel.

Referring to figure 25, there is shown a second embodiment of a fluidic valve 2500. It can be appreciated from figure 25, in contrast to the first embodiment shown in figure 22, that lower inner wall 2502 of the supply nozzle 2202 extends to form a continuous surface with the second lip 2224 of the outlet channel 2206 and the second lip 2223 of the control nozzle 126. It can be seen that the second lip 2223 of the control nozzle is displaced a distance, m , that is, a predeterminable distance, from the plane 136 containing the wall of the first 2222 lip of the outlet channel 2206.

All other features shown in the second embodiment that are common to both the second embodiment and the first embodiment operate in substantially the same manner as described above in relation figures 22 to 24. However, the advantage gained by having the wall 2502 extending from the supply nozzle to the inlet 2220 of the outlet channel 2206 is that there is less opportunity for contamination of the supply fluid by contaminants present in the vent 2402. It can be appreciated that contamination is only possible from one side of the flow supply fluid 2204 to the outlet channel 2206.

Referring to figure 26 there is shown a fluidic valve 2600 a third embodiment of according to the present invention. The description given above in relation to the embodiment shown in figure 22 is equally applicable to the common features of the embodiment shown in figure 26. It can be seen from figure 26 that the inclination angles, α and β , are substantially smaller as compared to

those inclination angles of figure 22. Further, it can be appreciated that the predeterminable distance, m , of the control nozzle from the entrance to the outlet channel 2206 is greater than the corresponding distance shown in figure 22. An advantage of having the control nozzle further downstream is that the control flow can act on the fluid in the outlet channel in a manner similar to the action of a jet pump and the generated backflow in the closed state is larger. Alternatively, for a required level of backflow, the control flow used to generate that backflow may be reduced with increased downstream control nozzle distance. It can also be seen that the walls contained within the plane 2236 of figure 22 either side of the inlet to the outlet channel 2206 are no longer coplanar. It will be appreciated that the non-coplanar arrangement allows easier flow of the supply fluid into the vent with less hydraulic loss due to changes in direction of flow. Again, as shown in figure 22, the control fluid nozzle shown in figure 26 is arranged so that control fluid does not pass into the supply nozzle and does not interfere with the flow of supply fluid 2204 out of the supply nozzle 2202.

Referring to figure 27, there is shown a fourth embodiment of a fluidic valve 2700. Again, features common to the above embodiments will not be described in detail as they function in substantially the same manner or have the same effect. The significant differences of the fourth embodiment over the above embodiments are, firstly, that the outlet channel inclination angle, β is zero, that is, the supply nozzle axis 2210 and the outlet channel axis 2214 are colinear, and, secondly, the predeterminable distance, m , of the control nozzle from

the first lip 2222 of the inlet 2220 of the outlet channel 2206 is slightly increased. It will be appreciated that, in the closed state, an increase in the value of m leads to increased entrainment. In the
5 embodiment shown in figure 27 where $\beta=0$, an acceptable value of m may correspond to twice the outlet channel width. However, if the sum of $\alpha+\beta$ is close to zero, such as shown in figure 22, then it may be possible to utilise a larger value of m . For example, the value of m may be
10 seven or eight times the outlet channel width.

Referring to figure 28 there is shown a perspective view of the embodiment of the fluidic valve shown in figure 27. The valve 2700 is shown in the closed state.
15 The control fluid 2228 forms a barrier 2702 which prevents the supply fluid 2204 entering the outlet channel 106. The embodiment shown in figure 28 corresponds to that also shown in figure 26. It can be appreciated from the perspective drawing how the devices
20 can be manufactured, that is, by constant depth etching 2704.

Figure 29 shows a fluidic valve 2900 according to a fifth embodiment of the present invention. Again,
25 features that are common to this fluid valve 2900 and the above described fluidic valves will not be described in detail as they perform substantially the same function and/or operate in substantially the same manner except where indicated to the contrary below. It can be
30 appreciated from figure 29 that the axis of the outlet channel 2206 and the axis of the control nozzle 2226, are colinear. Therefore, the outlet channel inclination angle and the supply channel inclination angle are equal

in magnitude but of opposite sign. The outlet channel 106 is divided into two branches, that is, first 2206A and second 2206B branches. The fluidic valve 2900 comprises a more complex vent which is divided into three
5 parts 2902, 2904 and 2906. Advantageously, the embodiment can provide a very long entrainment interface, 2908 and 2910, that is, the value of m can be high. A further advantage is that there are entrainment interfaces on both sides of the control fluid flow.

10

The control nozzle is clearly located within the outlet channel 2206, and is disposed at a relatively large distance, m , from the inlet 2220 of the outlet channel 2206. The relatively large distance between the
15 inlet 2220 of the outlet channel 2206 and the control nozzle 2226 results in relatively large entrainment interfaces 2908 and 2910 having larger surface, or entrainment, areas. Advantageously, this results in increased entrainment efficiency in drawing fluid from
20 both branches 2206A and 2206B of the outlet channel 2206 in the event of closure of the valve by flow of the control fluid 2228.

Figure 30 illustrates a still further embodiment of
25 a fluidic valve 3000. Again, functionally equivalent or identical aspects of the fluidic valve 3000 that are common to the above embodiments will not be described in detail. The fluidic valve 3000 comprises a supply nozzle 2202, a control nozzle 2226 and an outlet channel 2206 as
30 well as a vent 3002. The vent 3002 is used to draw fluid away from the fluidic valve via an outlet 3004 in a plate (not shown) disposed above the fluidic valve 3000. It can be seen that the supply nozzle and the control nozzle

share a common wall 3006 which, again, has the advantage of reducing contamination of the fluid flowing into the outlet channel 2206. It can be appreciated that figure 30 shows a number of relative dimensions of the features of the embodiment. All of the relative dimensions are given with respect to the supply nozzle width. The supply nozzle width is b . The width of the inlet to the vent is $3.69b$. The width of the outlet channel inlet is $0.97b$. the radii of the lips of the outlet channel inlet, one of which lips is common to the vent lip, are both $r_1=0.29b$. The radius of the other outlet channel lip is $r_2=1.47b$. The width of the control nozzle is $1.54b$. The length of the wall that is common to the supply nozzle and the control nozzle is $2.84b$. Preferably, the aspect ratio is one or more.

Referring to figure 31 there is shown a sampling unit 3100. It can be appreciated that only a portion of the sampling unit is illustrated, that is, only three fluidic valves 3102, 3104 and 3106. A fluidic valve 3104 is open whereas the other fluidic valves 3102 and 3106 are closed. Referring to the first fluidic valve 3102, it can be seen that supply fluid 3108 is being deflected by control fluid 3110 into a common supply fluid vent 3112, that is, the channel running vertically past all valves. The control fluid 3114 contained within the control nozzle 3116 of the second fluidic valve 3104 is stationary and does not, therefore, impede the flow of supply fluid 3118 into both branches of the outlet channel 3120 and 3122. The superfluous supply fluid 3124 and 3126 is also carried into the vent 3112. Each of the fluidic valves 3102 to 3106 has opposite the inlet of the outlet channel 2206 further vents 3128 to 3132 that allow

the control fluid from a corresponding fluidic valve to be vented.

Additionally, in the case of prolonged supply of supply fluid from, for example, the second fluidic valve supply nozzle 3118, it can be appreciated that the superfluous supply fluid 3124 and 3126 will also be drawn into the vents 3128 to 3132 that are disposed opposite the inlets of the outlet channel 2206. The embodiment of the fluidic valve 3100 shown in figure 31 can optionally close a fluidic valve 3102 to 3106 under the action of jets of control fluid rather than under the action of laminar flow at low Reynolds numbers. As discussed above in relation to the embodiments shown in figure 8, the jets of control fluid can optionally be made to form vortices along the entrainment interfaces (not shown). These vortices draw the fluid from the outlet channel 106 into the vent 3112 and into the vents 3128 to 3132. As the supply fluid 3118 is carried into the two branches 3120 and 3122 of the corresponding portion of the outlet channel fluid is drawn from the outlet channel by the flow of control fluid from the other two control nozzles 3110 and 3136.

Figure 32 illustrates a sampling unit 3200 which uses fluidic valves 3202 to 3232 as illustrated in figure 30. It can be seen that each valve 3202 to 3232 has a control inclination angle, α , that is positive and an outlet channel inclination angle, β , that is negative. It can be appreciated that the valves 3202 to 3232 are radially arranged and control the flow of fluid supplied by first 3234 to sixteenth 3264 supply nozzles. Each of the supply nozzles 3234 to 3264 are individually fed by

fluids, such as, for example, reaction products from sixteen corresponding reactors (not shown). The outlet channel, or common outlet space, is arranged to be connected to an analyser (not shown). It can be appreciated that the embodiment of the sampling unit 3200 shown in figure 32 takes up a smaller area than a linear equivalent of such a sampling unit, such as shown in figure 31.

10 In a laboratory model of the above embodiments, the following dimensions were used: nozzle width 0.34 mm, the supply fluid was hot SyngasTM having a viscosity of 50×10^{-6} m²/s and a nozzle exit velocity of 5 m/s so that the Reynolds number was 34. However, typical values in
15 microfluidic applications would be: nozzle/channel widths of 10-100µm, nozzle and channel depths of 10-100µm, viscosities of $1 \cdot 10^{-6}$ - $20 \cdot 10^{-6}$ m²/s and nozzle exit velocities of 0.1-1 m/s.

20 It will be appreciated that the valves in the above embodiments are manufactured by, for example, etching layers of suitable material. Accordingly, the flow of fluids within the valves are or can be arranged to be normal to the channels via which the fluid is supplied to
25 a valve, vented from a valve and/or output from a valve. It is clear from, for example, the embodiment shown in figure 30 that the supply fluid 2204 is supplied via an appropriately etched layer or plate that is disposed above the valve plate or layer. Similarly, the vent 3002
30 has an outlet 3004 that is disposed in a layer that is adjacent to the layer containing the valve features. Furthermore, the supply nozzle 2202 is fed from a layer that is adjacent, but vertically disposed relative to,

the layer which carries the supply fluid 2204 to the supply nozzle 2202. It can be appreciated that the same applies in relation to the control nozzle and the supply of control fluid.

5

The magnitudes of the fluid flows of conventional fluidic valves are such that the supply fluid flow is significantly greater than the control fluid flow. However, the embodiments of the present can equally well
10 use fluid flow magnitudes in which the control fluid flow is at least equal to or significantly greater than the supply fluid flow. In some embodiments that control fluid flow may be at least 10 times greater than the supply fluid flow. It is envisaged that the above
15 embodiments may utilise control flows that are between 0.1 and 100 times that of the supply flow.

It will be appreciated that the embodiments of the present invention can be fabricated using a semiconductor
20 manufacturing technology or other etching technology such as, for example, the etching technology provided by Microponent Limited, 30 Curzon Street, Birmingham, B4 7XD, England.

25 It is envisaged that embodiments of the present invention may be realised in which sixteen valves are etched in a 78 mm stainless steel circular plate having a thickness of 0.254 mm. In some embodiments, the cavities can be etched to a depth of 0.1016 mm. Preferably, the
30 widths of the cavities, that is the supply nozzle widths, are 0.34 mm. The other dimensions are obtained by using the value of $b=0.34$ mm in the above and, in particular, in figure 30. However, although the embodiment of, for

example, figure 30 has the above dimensions, embodiments of the present invention are not limited thereto. Embodiments can be realised in which the dimensions are limited by the anticipated size of particles that may flow through the valves. For example, with special cleaning and filtering, embodiments can be realised in which the dimensions are 0.1 times that of the above embodiments. The upper limit to the dimensions of the embodiment is determined by what may be reasonably considered to be "microfluidics" by the skilled man. It is thought that embodiments having dimensions that are 10 times greater than the above embodiments may be better implemented using a turbulent flow regime. The operating parameters of the above embodiments can vary according to application. For example, it is envisaged that the embodiments may be operated at 0.1 to 100 times atmospheric pressure. The upper limit of the operating pressure is determined in part by the material from which the embodiments are realised. Similarly, the operating temperature of the devices can vary according to application. Embodiments are envisaged in which the operating temperature may be between 300 K and 1000 K. Again the operating temperature is limited in part by the material from which the embodiments are manufactured. For example, if refractory materials are used, even higher operating temperatures may be realised. The flow rates of the embodiments will vary according to the application of the valves and the fluid properties. For example, mass flow rates of between 10^{-9} kg/s and 10^{-3} kg/s are envisaged.

The reader's attention is directed to all papers and documents which are filed concurrently with or previous

to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

5

All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

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Each feature disclosed in this specification (including any accompanying claims, abstract and drawings), may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

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The invention is not restricted to the details of any foregoing embodiments. The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

25

CLAIMS

1. An assembly comprising a plurality of reactors for supplying reactor products to a common outlet channel via respective fluidic control valves, the valves being arranged to pass or prevent the flow of reactor products into the common outlet channel using respective control fluids to block or open the path of the reactor products to the common outlet channel.
2. An assembly as claimed in any preceding claim in which the fluidic control valves comprise part of a fluidic multiplexer as claimed in any of claims 14 to 24.
3. An assembly as claimed in any preceding claim comprising a mixer for combining at least two fluid flows before supplying the mixed fluid flows to the plurality of reactors.
4. An assembly as claimed in either of claims 3 and 4 in which the mixer is a mixer as claimed in any of claims 25 to 71.
5. An assembly as claimed in any preceding claim comprising a distributor for distributing fluids to at least one of the plurality of reactors.
6. An assembly as claimed in claim 4 in which the distributor is a distributor as claimed in any of claims 9 to 13.
7. An assembly as claimed in claim 2 in which at least

one of the plurality of reactors is a reactor as claimed in any of claims 76 to 89.

- 5 8. An assembly substantially as described herein with reference to and/or as illustrated in the accompanying drawings.
- 10 9. A fluid distributor comprising at least one inlet for receiving a fluid and a corresponding outlet for outputting the fluid and a channel coupled between the inlet and outlet for varying the pressure of the fluid such that the pressure of the fluid at the inlet has a predeterminable relationship to the pressure of the fluid at the outlet.
- 15 10. A fluid distributor as claimed in claim 9 in which the fluid at the inlet is at a greater pressure than the fluid at the outlet.
- 20 11. A fluid distributor as claimed in either of claims 9 and 10 in which the channel follows a non-rectilinear path.
- 25 12. A fluidic distributor as claimed in claim 11 in which the non-rectilinear path is at least one of a square-wave shape or a serpentine shape.
- 30 13. A fluidic distributor substantially as described herein with reference to and/or as illustrated in the accompanying drawings.
14. A fluidic multiplexer for supplying to a common outlet channel (112) one fluid selected from at

least a first fluid channel and a second fluid channel each for carrying respective first (102) and second (104) fluid flows; the multiplexer (100) comprising a first fluidic valve (114) to prevent
5 flow of the first fluid from the first fluid channel (102) to the common outlet channel (112) in response to flow of a first control fluid from a first control inlet (154) and a second fluidic valve (116) to prevent the flow of the second fluid (104) from
10 the second fluid channel to the common outlet channel (112) in response to flow of a second control fluid from a second control inlet (156).

15. A fluidic multiplexer as claimed in claim 14 in
15 which the first fluidic valve (114) comprises a first vent (124) arranged to allow flow of the first fluid (102) through the first vent (124) in response to the first control fluid preventing flow of the first fluid (102) to the common outlet channel
20 (112).

16. A fluidic multiplexer as claimed in either of claims 1 and 2 in which the second fluidic valve (116) comprises a second vent (126) arranged to allow flow
25 of the second fluid (104) through the second vent (126) in response to the second control fluid preventing the flow of the second fluid (104) to the common outlet channel (112).

30 17. A fluidic multiplexer arranged to control selectably the flow of a first fluid (102) and a second fluid (104) into a common outlet channel (112) using first (114) and second (116) fluidic valves, the first

fluidic valve (114) having a first inlet to supply the first fluid (102) to a first outlet channel and a first control inlet (154) to prevent flow of the first fluid (102) to the first outlet channel; the
5 second fluidic valve (116) having a second inlet to supply the second fluid (104) to a second outlet channel and a second control inlet to prevent flow of the second fluid (104) to the second outlet channel; the first and second outlet channels being
10 arranged to feed the common outlet channel (112).

18. A fluidic multiplexer as claimed in any of claims 14 to 17 further comprising a pressure regulator for establishing the pressure in the outlet channel to
15 be a predeterminable pressure.

19. A fluidic multiplexer as claimed in any of claims 14 to 18 further comprising a pressure regulator for
changing the pressure of at least one of either of
20 the first (102) and second (104) fluids from respective first and second pressures to a selectable pressure prior to feeding the common outlet channel (112).

25 20. A fluidic multiplexer as claimed in any of claims 14 to 19 in which the direction of flow of the control fluid (104) is arranged to oppose the direction of flow of the supply fluid (102).

30 21. A fluidic multiplexer as claimed in of claims 14 to 20 in which the dimensions of the channels and inlets are arranged such that the fluids flows carried therein have associated Reynolds numbers

that are less than 100.

22. A fluidic multiplexer as claimed in claim 21 in which the associated Reynolds numbers are less than 40.

23. A fluidic multiplexer as claimed in any of claims 14 to 22 in which the first fluidic valve (114) operates in anti-phase with the second fluidic valve (116).

24. A fluidic multiplexer substantially as described herein with reference to and/or as illustrated in any of the accompanying drawings.

25. A fluidic mixer comprising a first nozzle and a second nozzle to feed a cavity having at least two exit channels; the first and second nozzles being arranged to produce mutually opposing first and second fluid flows that form in at least one exit channel interleaved layers of the first fluid and the second fluid.

26. A mixer comprising a first nozzle and a second nozzle that feed a cavity having at least two exit channels; the first and second nozzles being arranged to produce mutually opposing flows of a first fluid and a second fluid that are arranged to oscillate to feed in an alternating manner the two exit channels.

27. A mixer as claimed in either of claims 25 to 26 that is arranged to produce a first feedback loop fluid

flow of at least the first fluid such that the first feedback loop fluid flow influences the flow of the first fluid from the first nozzle.

5 28. A mixer as claimed in claim 27 in which the influence of the first feedback loop fluid flow on the first fluid is exerted at the first nozzle exit.

10 29. A mixer as claimed in either of claims 27 and 28 in which the first feedback loop fluid flow causes the first fluid flow to form second feedback loop fluid flow.

15 30. A mixer as claimed in claim 29 in which the turning sense of the first feedback loop fluid flow is opposite to the turning sense of the second feedback loop fluid flow.

20 31. A mixer as claimed in either of claims 29 and 30 in which the first and second feedback loop fluid flows are disposed on opposite sides of colinear axes of the first and second nozzles.

25 32. A mixer as claimed in any claims 25 to 31 that is arranged to produce a feedback loop fluid flow of at least the second fluid such that the feedback loop fluid flow influences the flow of the second fluid from the first nozzle.

30 33. A mixer as claimed in any of claims 27 to 32, in which the influence exerted causes the first and second fluid flows to oscillate and feed in an alternating manner different ones of the two exit

channels.

34. A fluidic mixer comprising a first inlet and a second inlet for feeding respective first and second nozzles, the nozzles having substantially colinear axes and being arranged to produce mutually opposing first and second fluid flows within a cavity, the cavity having two exit channels, the nozzles having profiled lips that protrude into a volume and define first and second exit channels.
35. A fluidic mixer as claimed in claim 34 in which the width of at least one of the first and second nozzles is b .
36. A mixer as claimed in either of claims 34 and 35 in which at least one of the first and second has a predeterminable aspect ratio, λ .
37. A mixer as claimed in any of claims 34 to 36 in which the depth of the mixer has a predeterminable value, h .
38. A mixer as claimed in any of claims 25 to 37 in which at least one of the first and second nozzles comprises a nozzle channel having a predeterminable length.
39. A mixer as claimed in claim 38 in which the channel length is given by $0.5b \leq l_2 \leq 10b$, and preferably $l_2 = 1.4b$, where b is the width of a respective nozzle.
40. A mixer as claimed in either of claims 38 and 39 in

which the first nozzle comprises a first inlet of a predetermined width.

41. A mixer as claimed in claim 40 in which the
5 predetermined width is given by $0.005 \text{ mm} \leq b \leq 10 \text{ mm}$.
42. A mixer as claimed in either of claims 40 or 41 in
10 which the first inlet comprises a first profiled surface which narrows the first inlet from the predetermined width to the nozzle width.
43. A mixer as claimed in claim 42 in which the first
15 profiled surface comprises a first inflexion between a first radius and second radius to form a wall between a respective nozzle exit and a respective exit channel.
44. A mixer as claimed in claim 43 in which the first
20 inflexion comprises a first inflexion linear portion that is substantially linear portion between the first and second radii.
45. A mixer as claimed in either of claims 43 and 44 in
25 which the first radius has a predeterminable value given by $r_1 = 2.9b$, where b is the nozzle width at least one of the first and second nozzles.
46. A mixer as claimed in any of claims 43 to 45 in
30 which the second radius has a predeterminable value given by $r_2 = 2.3b$, where b is the nozzle width a respective nozzle.

47. A mixer as claimed in any of claims 38 to 46 in which the at least one of the first and second nozzles has a second profiled surface.

5 48. A mixer as claimed in claim 47 in which the second profiled surface is a second inflexion between a third radius and fourth radius to form a wall between a respective nozzle exit and a respective exit channel.

10

49. A mixer as claimed in claim 39 in which the inflexion comprises a second inflexion linear portion that is substantially linear between the third and fourth radii.

15

50. A mixer as claimed in either of claims 48 and 49 in which the third radius has a predeterminable value given by $r_3 = 3.5b$, where b is the nozzle width of at least one of the first and second nozzles.

20

51. A mixer as claimed in any of claims 48 to 50 in which the fourth radius has a predeterminable value given by $r_4 = 0.3b$, where b is the nozzle width a respective nozzle.

25

52. A mixer as claimed in any of claims 25 to 51 in which the first inflexion linear portion is inclined at a predetermined angle relative to the axis of a respective nozzle.

30

53. A mixer as claimed in claim 52 in which the predetermined angle is between 20° and 60° .

54. A mixer as claimed in claim 53 in which the predetermined angle is 45° .
55. A mixer as claimed in any of claims 25 to 54 in which the second inflexion linear portion is inclined at a predetermined angle relative to an axis of a respective nozzle.
56. A mixer as claimed in claim 55 in which the predetermined angle is between 20° to 60° .
57. A mixer as claimed in claim 56 in which the predetermined angle is 45° .
58. A mixer as claimed in any of claims 25 to 57 in which the cavity provides a predetermined separation between the exits of the first and second nozzles.
59. A mixer as claimed in claim 58 in which the predetermined separation is determined by $s=3b$, where b is the width of a respective nozzle.
60. A mixer as claimed in any of claims 25 to 59 in which the fluid flow rate of fluid in at least one of the two exits channels is selected according to a molecular diffusion path length of the first and second fluids.
61. A mixer as claimed in any of claims 25 to 60 in which the first and second fluids are arranged to oscillate at a predetermined frequency.
62. A mixer as claimed in claim 61 in which the

predetermined frequency has a value in the range of 0.2 Hz to 100 kHz.

63. A mixer as claimed in either of claims 62 and 38 in which the predetermined frequency is given by

$$\text{frequency } f = \frac{1}{\Delta t_p} = \frac{\beta w}{2b(\mu + \sigma)}$$

64. A mixer as claimed in any of claims 25 to 63 in which the Reynolds number of at least one of the first and second fluid flows is less than 450.

65. A mixer as claimed in claim 64 in which the Reynolds number of at least one of the first and second fluid flows is less than 100.

66. A mixer as claimed in claim 65 in which the Reynolds number of at least one of the first and second fluid flows is less than 10.

20

67. A mixer as claimed in any of claims 25 to 66 in which at least one of the first and second fluid flows has a Strouhal number of $0.01 \leq Sh \leq 0.4$.

- 25 68. A mixer as claimed in claim 67 in which at least one of the first and second fluid flows has a Strouhal number of $Sh = 0.04$.

69. A fluidic mixer substantially as described herein with reference to and/or as illustrated in the accompanying drawings.

30

70. A mixer comprising a first mixer as claimed in any of claims 25 to 69 arranged so that an exit channel of the first mixer is arranged to feed an inlet of a second mixer as claimed in any preceding claim.
- 5
71. A two-stage mixer comprising two primary mixers as claimed in any of claims 25 to 70 arranged to feed respective inlets of a secondary mixer as claimed in any preceding claim.
- 10
72. An assembly as claimed in any preceding claims which the fluidic valves comprise a fluidic control device or valve as claimed in any of claims 73 to
- 15
73. A fluidic control device for controlling the flow rate of a controlled fluid using a control fluid, the device comprising an outlet chamber having mutually facing inlet nozzles that are arranged to form mutually opposing streams of control fluid and controlled fluid to control the rate of flow of the
- 20
- controlled fluid.
74. A fluidic control device as claimed in claim 73, wherein the inlet nozzles are substantially coaxial.
75. A fluidic control device as claimed in any of claims 73 to 74 in which at least one of the inlet nozzles
- 25
- comprises a contraction part for receiving the controlled fluid and forming the controlled fluid into the stream of controlled fluid.
76. A fluidic control device as claimed in claim 75, further comprising between the contraction part and
- 30
- the outlet chamber an exit channel of substantially

constant cross section.

77. A fluidic control device as claimed in any of claims 73 to 76 in which the controlled fluid is arranged to have a pre-determined Reynolds number.
- 5 78. A fluidic control device as claimed in claim 77, wherein the pre-determined Reynolds number is less than or equal to 40, and preferably less than or equal to 10.
- 10 79. A fluidic control device substantially as described herein with reference to and/or as illustrated in the accompanying drawings.
- 15 80. A fluidic valve comprising first and second nozzles, having respective first and second axis, arranged to produce a first fluid flow and a second fluid flow, the first fluid flow being arranged to flow from the first nozzle to an outlet channel having an outlet access; a second fluid flow being arranged to prevent flow of the first fluid to the outlet channel.
- 20 81. A fluidic valve as claimed in claim 80, in which the first axis, second axis and outlet axis are coplanar.
- 25 82. A fluidic valve as claimed in either of claims 80 and 81, in which at least two of the first axis, second axis and outlet axis are not colinear.
- 30 83. A fluidic valve as claimed in any of claims 80 to 82, in which the first and second fluid flows being arranged such that the second fluid flow does not

flow into the first nozzle.

84. A fluidic valve as claimed in claim 83, in which the orientation of the first and second axis is such that the second fluid flow does not flow into the first nozzle.
85. A fluidic valve as claimed in any of claims 80 to 84 in which the second fluid flow is arranged to prevent a flow of fluid in the outlet channel in a first predetermined direction.
86. A fluidic valve as claimed in any of claims 80 to 85 in which the second fluid flow is arranged to induce flow of fluid in the outlet channel in a second predetermined direction; the second predetermined direction being opposite to the first predetermined direction.
87. A fluidic valve as claimed in claim 86 in which the mutual positions and orientations of the second nozzle and the outlet channel are arranged to induce the flow of fluid in the outlet channel in the second direction.
88. A fluidic valve as claimed in any of claims 80 to 87 in which an angle subtended by the second axis and the outlet axis is acute.
89. A fluidic valve as claimed in claim 88 in which the angle subtended by the second axis and the outlet axis has a value in the range of 0° to 45° .

90. A fluidic valve as claimed in any of claims 80 to 89 in which an angle subtended by the first axis and the second axis is at least obtuse.
- 5 91. A fluidic valve as claimed in claim 90 in which the angle subtended by the first axis and the second axis has a value in the range of 15° to 175° , preferably, the angle is substantially 90° .
- 10 92. A fluidic valve as claimed in claim 91 in which the angle subtended by the first axis and the second axis is 180° .
- 15 93. A fluidic valve as claimed in any of claims 80 to 92 in which the normal projection of the cross section of the second nozzle onto a plane normal to the second axis does not intersect the normal projection of the cross section of the first nozzle onto the plane normal to the second axis.
- 20 94. A fluidic valve as claimed in any of claims 80 to 93 in which the second fluid flow does not impede the flow of fluid out of the first nozzle.
- 25 95. A fluidic valve as claimed in any of claims 80 to 94 further comprising a vent or at least one vent arranged to allow flow of the first fluid through the vent in response to the second fluid flow preventing the flow of the first fluid into the outlet channel.
- 30 96. A fluidic valve as claimed in any of claims 80 to 95 in which the second fluid flow does not interfere

with the flow of the first fluid through and ultimately out of the first nozzle.

97. A method of controlling the flow of an outlet fluid stream fed from an inlet fluid stream, comprising the step of arranging for a control fluid stream to intersect the inlet fluid stream to prevent the inlet fluid stream feeding the outlet fluid stream thereby preventing the flow of the outlet fluid stream in a first predetermined direction.

98. A method of controlling the flow of an outlet fluid stream fed from an inlet fluid stream using a fluidic valve as claimed in any of claims 80 to 96.

99. A method of controlling the flow of an outlet fluid stream substantially as described herein with reference to and/or as illustrated in any of the accompanying drawings.

100. A valve substantially as described herein with reference to and/or as illustrated in the accompanying drawings.

101. A method of controlling a flow of fluid substantially as described herein with reference to and/or as illustrated in the accompanying drawings.

102. A reactor or microreactor comprising at least one inlet arranged to feed a first reactant to or into an entrance end of a reaction chamber; the reaction chamber having an exit end comprising a fluidic control device as claimed in any of claims 80 to 96

for controlling the flow rate of fluid through the reaction chamber.

103. A reactor or microreactor as claimed in claim 104 further comprising an actuator that is arranged to
5 feed the control fluid to the control nozzle 3.

104. A reactor or microreactor as claimed in claim 103 in which the actuator comprises a heater for controlling the temperature of the control fluid.

105. A reactor or microreactor as claimed in any of
10 claims 102 to 104 further comprising an outlet channel arranged to conduct fluid from the outlet chamber.

106. A reactor or microreactor as claimed in claim 105 further comprising a separator for separating the
15 control and controlled fluids.

107. A reactor or microreactor as claimed in any of claims 102 to 106 in which the control fluid is derived from the controlled fluid.

108. A reactor or microreactor as claimed in any of
20 claims 102 to 106 in which the control fluid is derived from the first reactant.

109. A reactor or microreactor as claimed in any of claims 102 to 108 further comprising a heater for heating the reaction chamber to a pre-determined
25 temperature and/or for controlling the temperature of the reaction chamber.

110. A reactor or microreactor as claimed in any of claims 102 to 109 further comprising a heat exchanger for controlling the temperature of the

control fluid.

111. A reactor or microreactor as claimed in any of claims 102 to 110 further comprising a pump for controlling the pressure of the control fluid.
- 5 112. A reactor or microreactor as claimed in any of claims 102 to 111, wherein the inlet nozzles are separated by a pre-determined distance.
113. A microreactor or reactor as claimed in any of claims 102 to 112, where in the pre-determined
10 distance is related to the width of the inlet nozzle, preferably 2-7 times the width of the inlet channel.
114. A reactor or microreactor as claimed in any of claims 102 to 113 in which the outlet chamber
15 comprises an outlet opening positioned to allow fluid flow in a direction normal to a plane containing the outlet chamber and/or the reaction chamber.
115. A reactor or microreactor substantially as described
20 herein with reference to and/or as illustrated in the accompanying drawings.
116. A method for controlling the rate of flow of a controlled fluid using a control fluid, the method comprising the steps of forming the controlled fluid
25 and the control fluid into mutually facing streams of fluid injected into a fixed geometry chamber.
117. A method for controlling the rate of flow of a controlled fluid using a control fluid substantially as described herein with reference to and/or as

illustrated in the accompanying drawings.

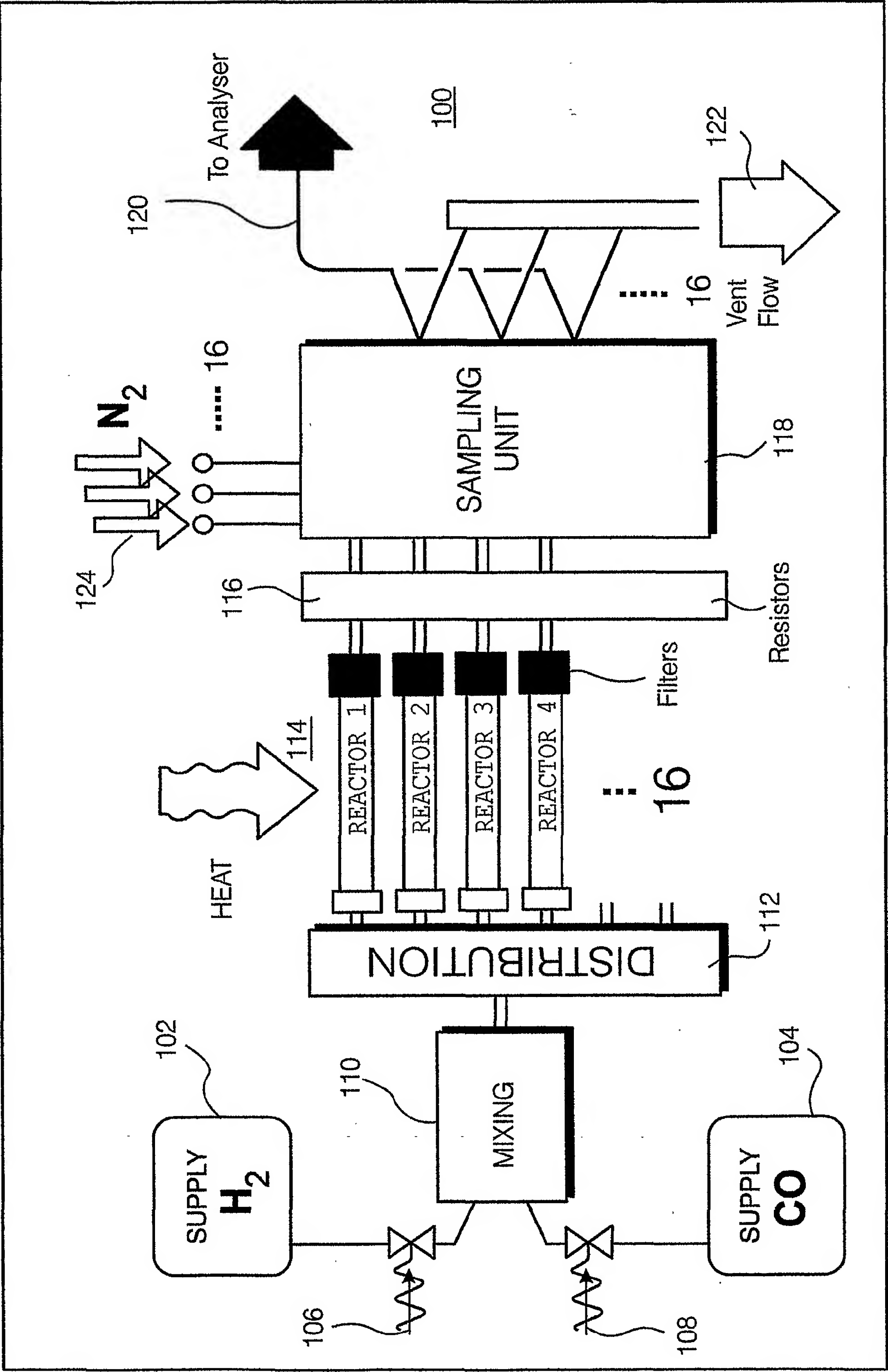


Fig. 1

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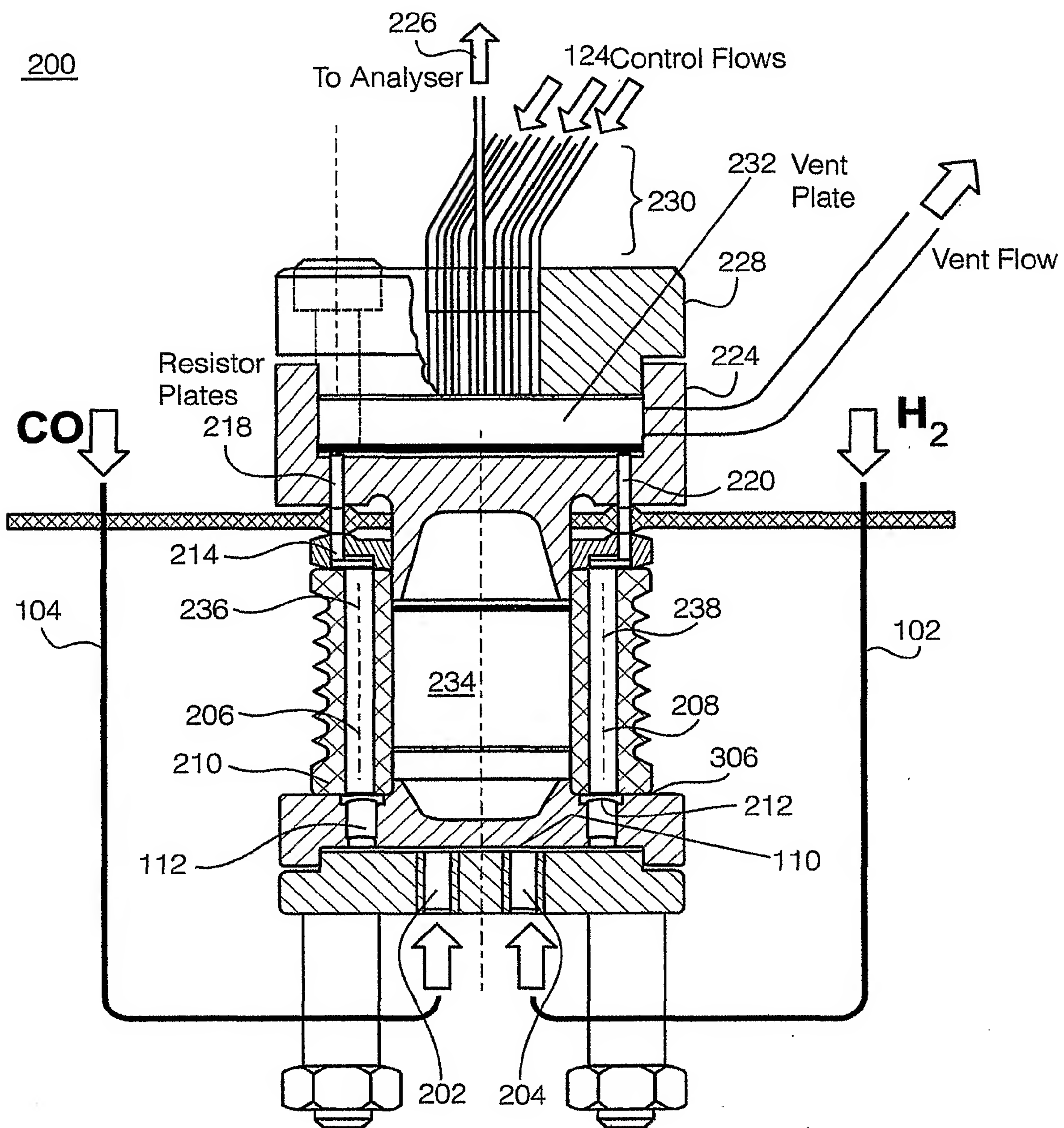


Fig. 2a

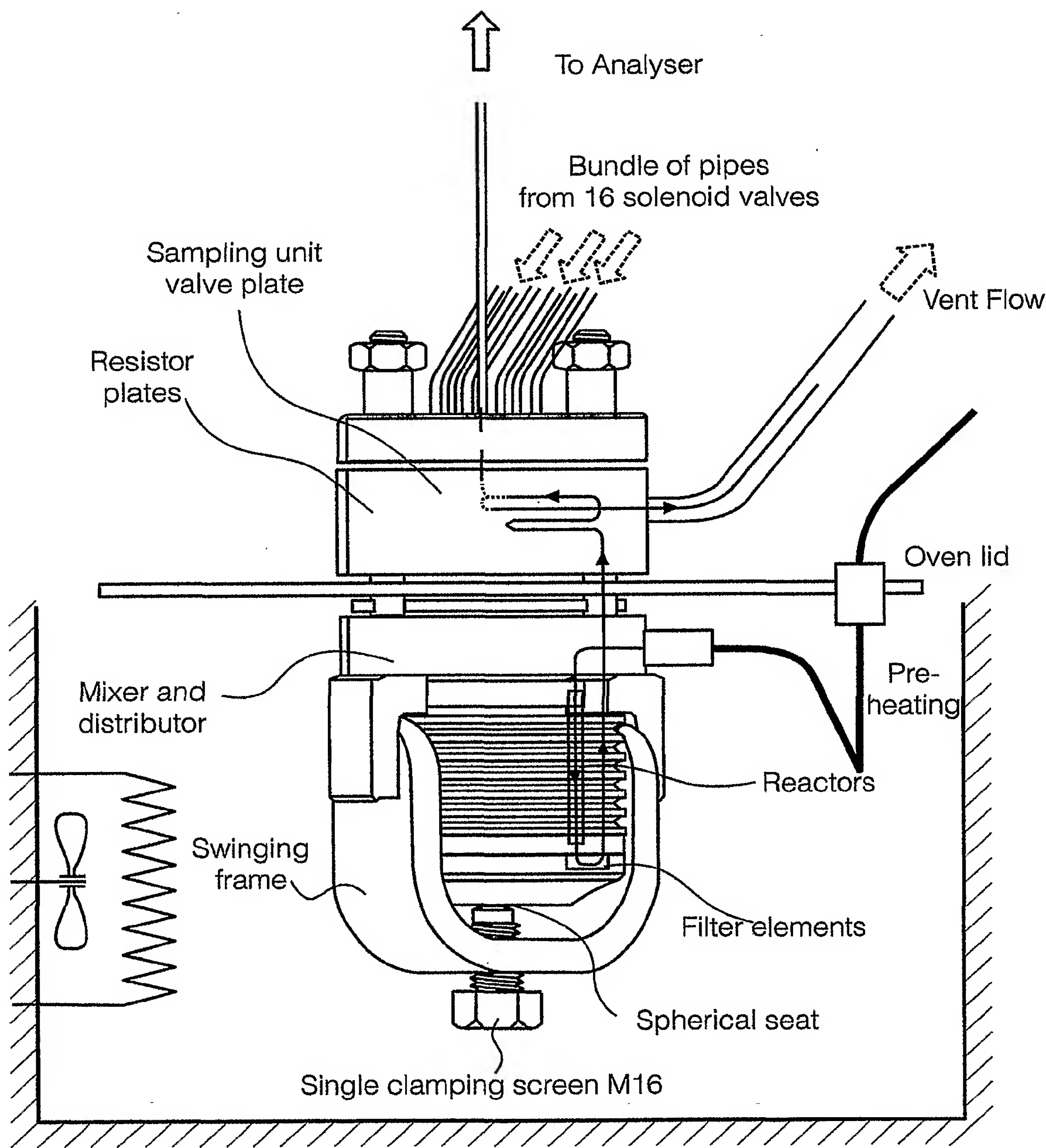


Fig. 2b

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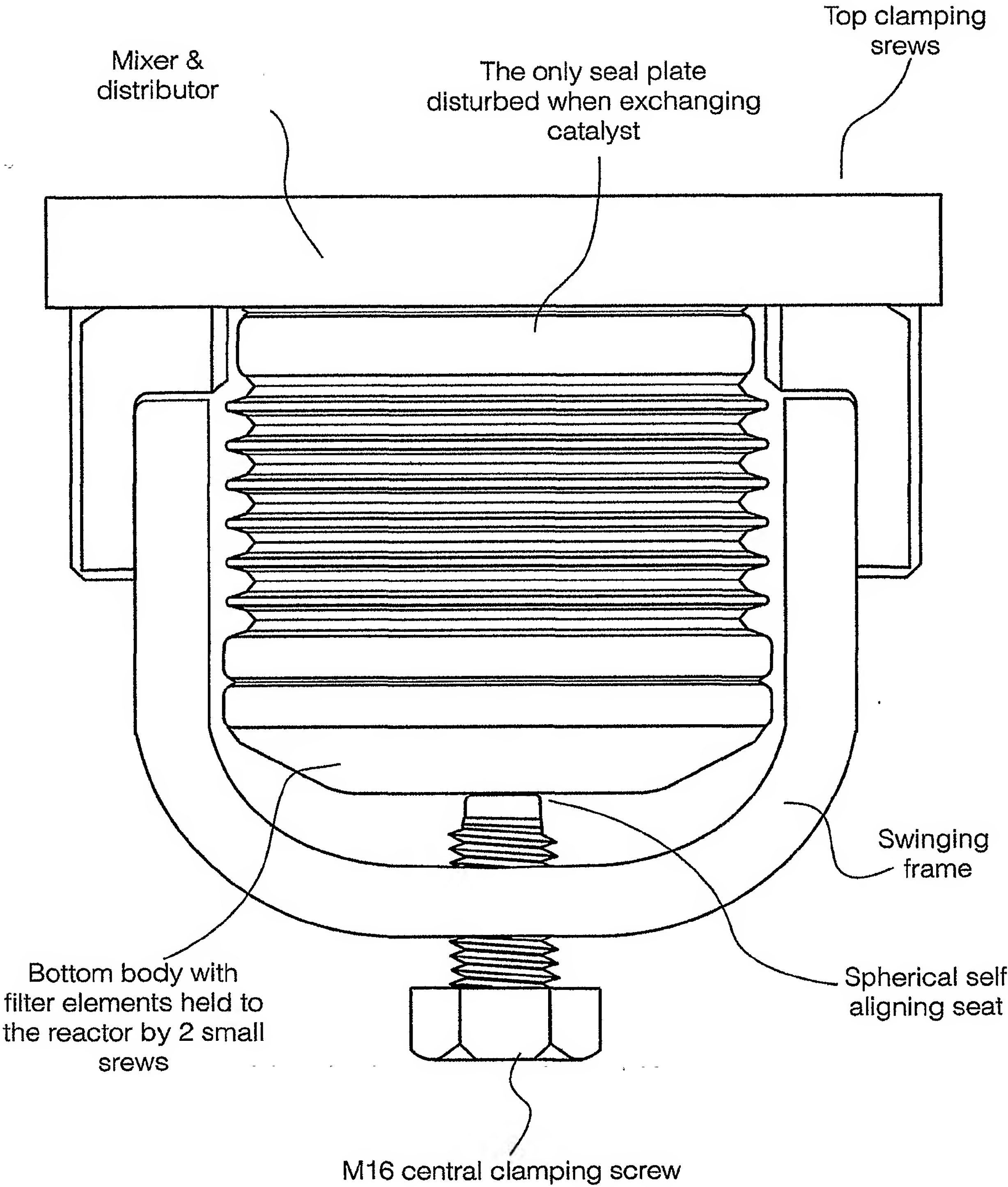


Fig. 2c

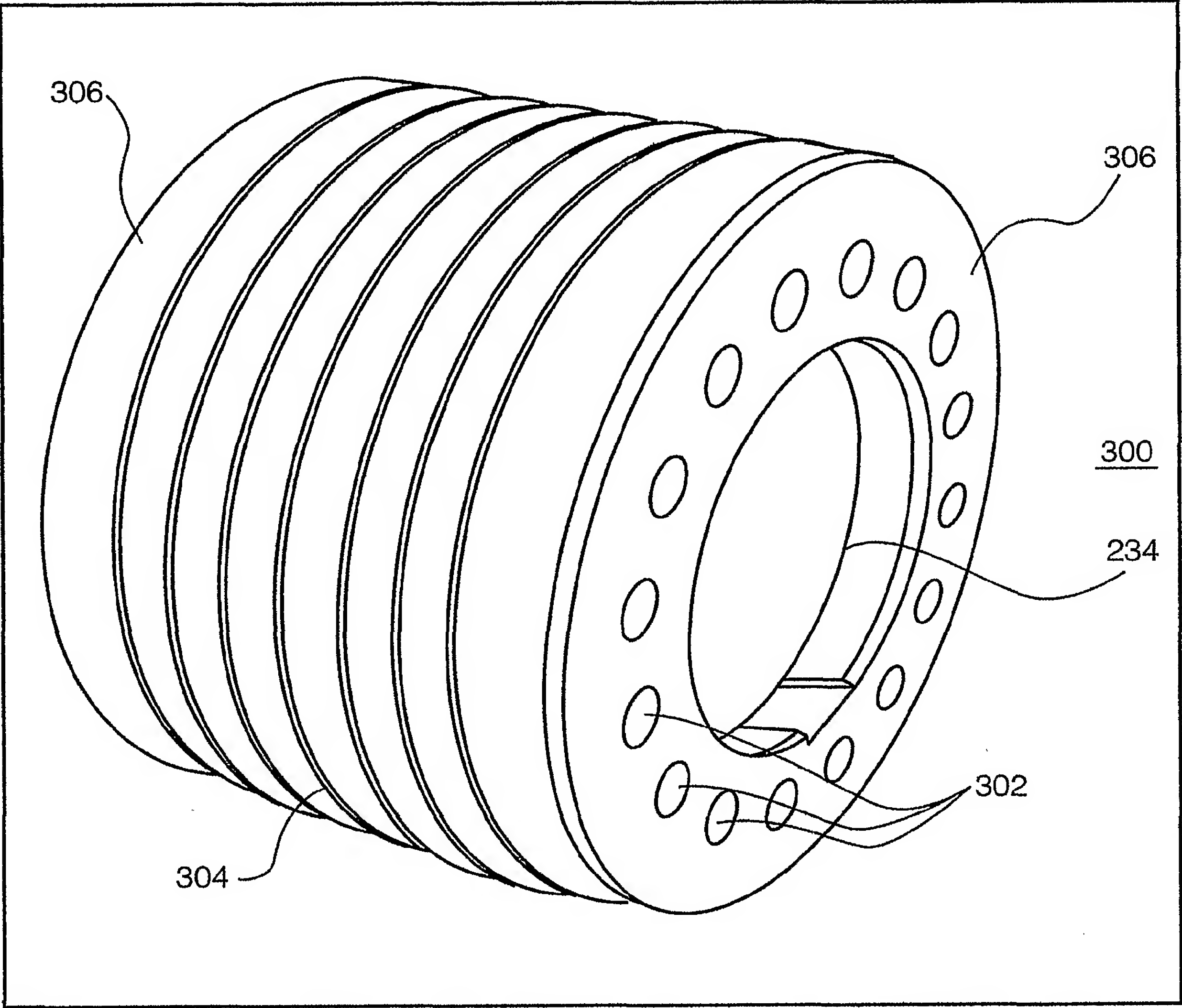


Fig. 3

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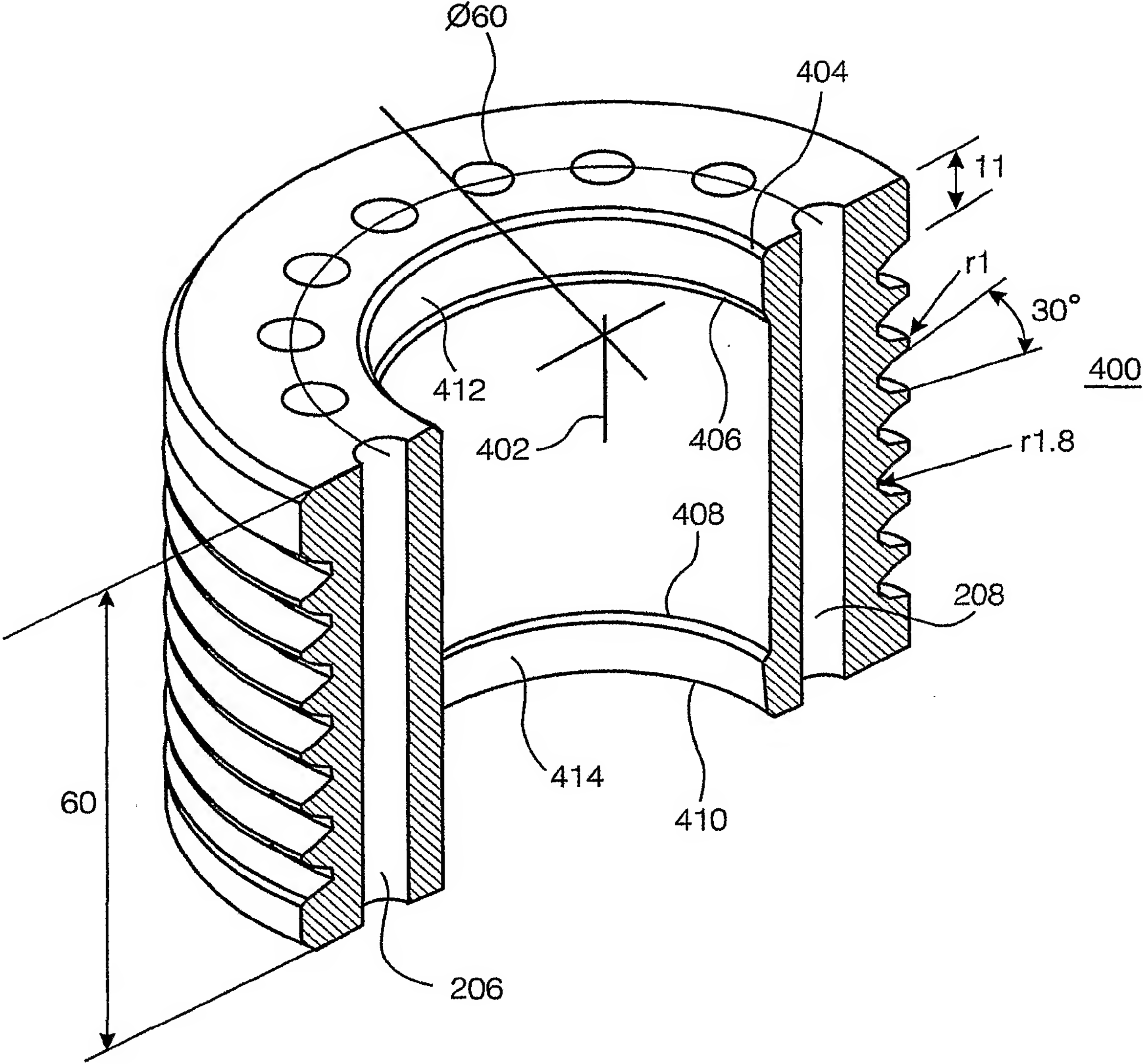


Fig. 4a

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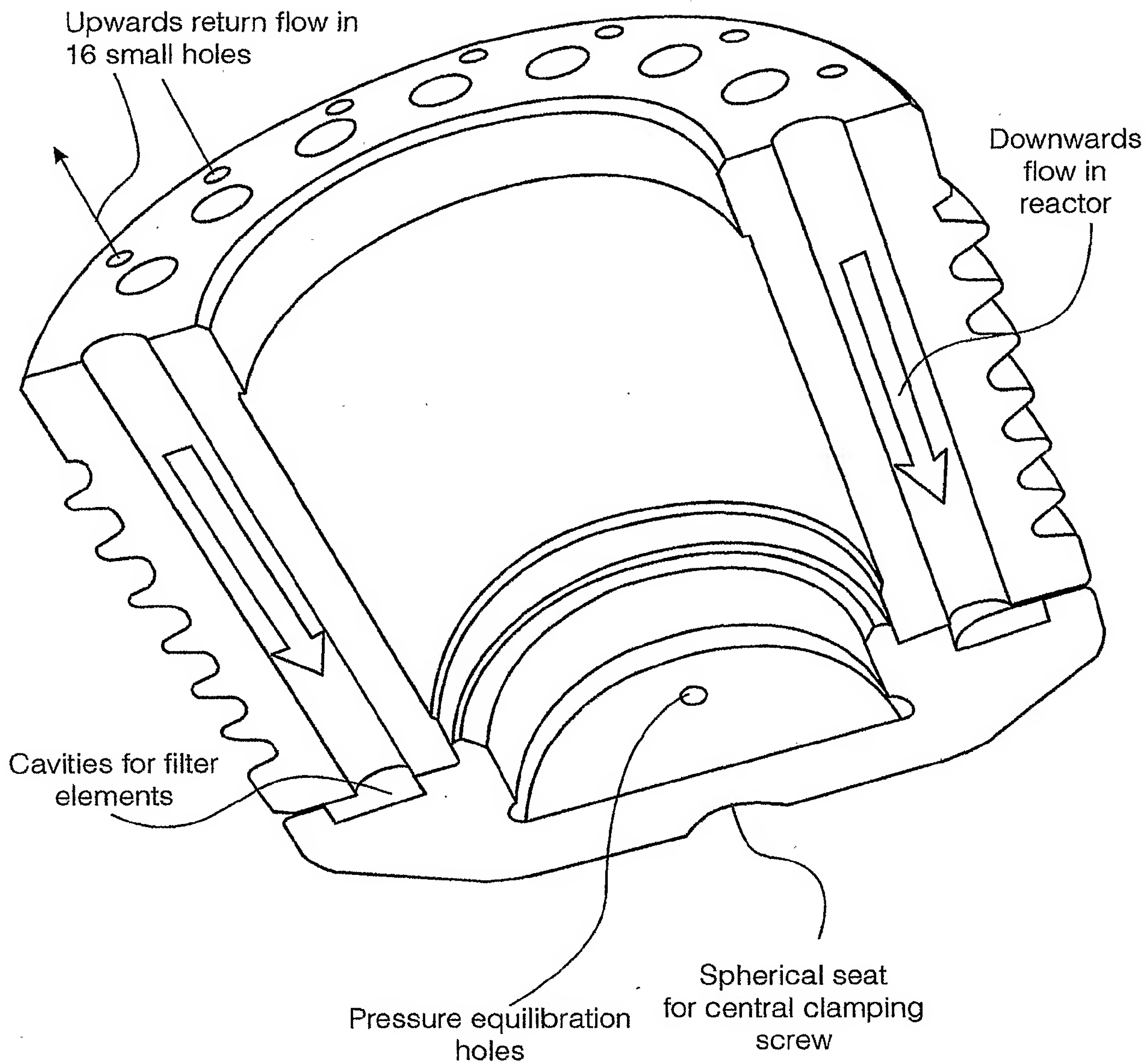


Fig. 4b

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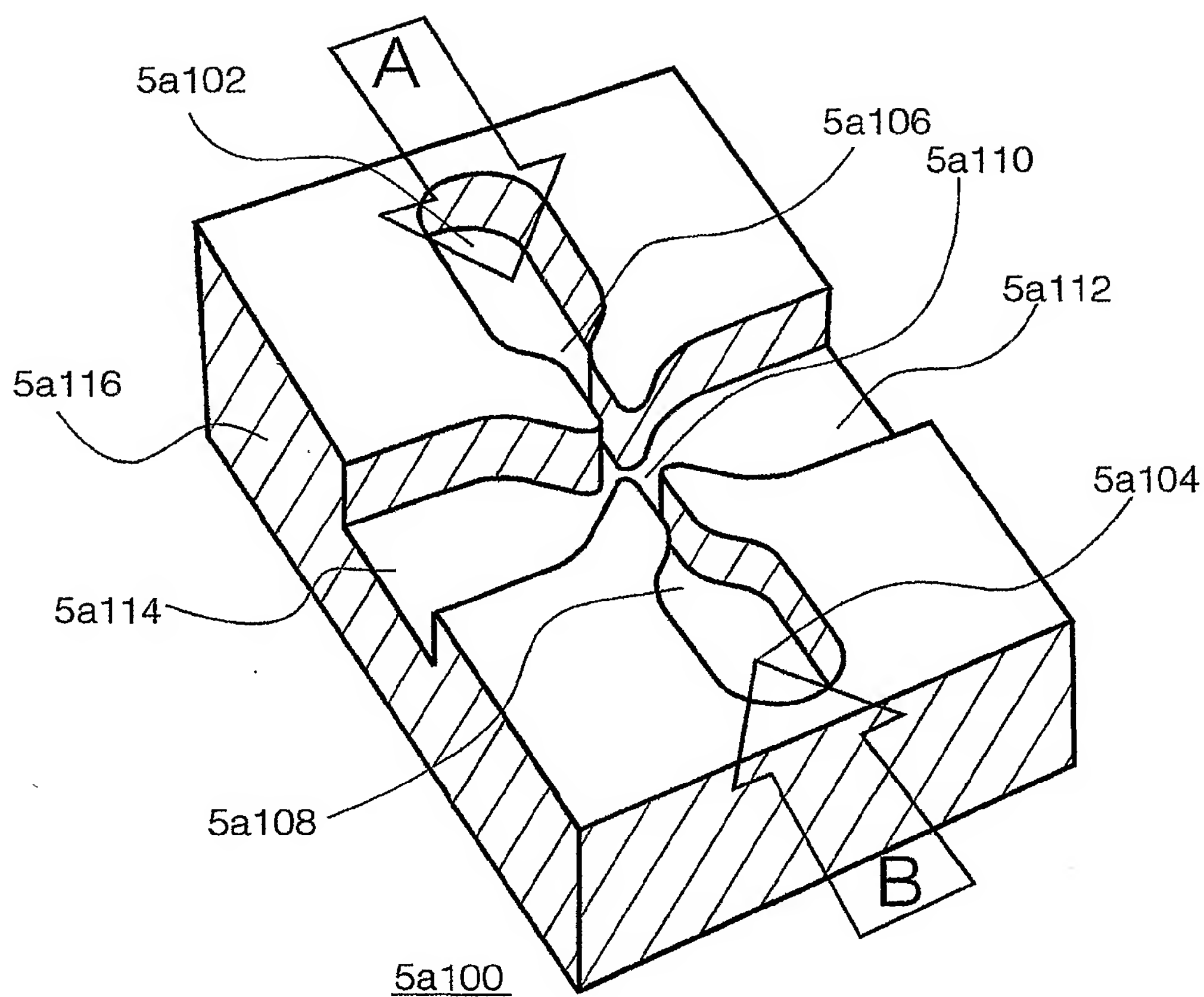


Fig. 5a

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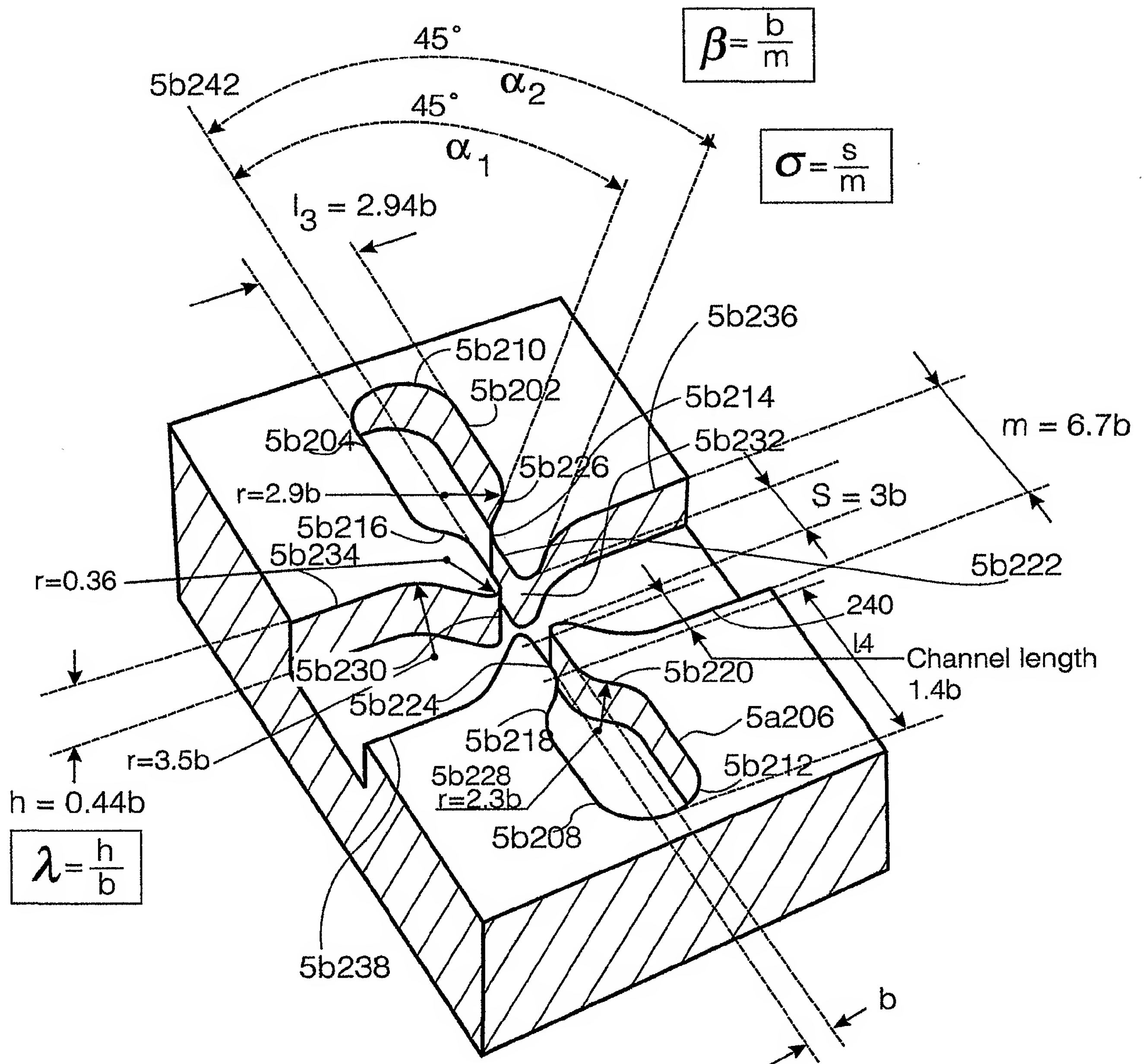


Fig. 5b

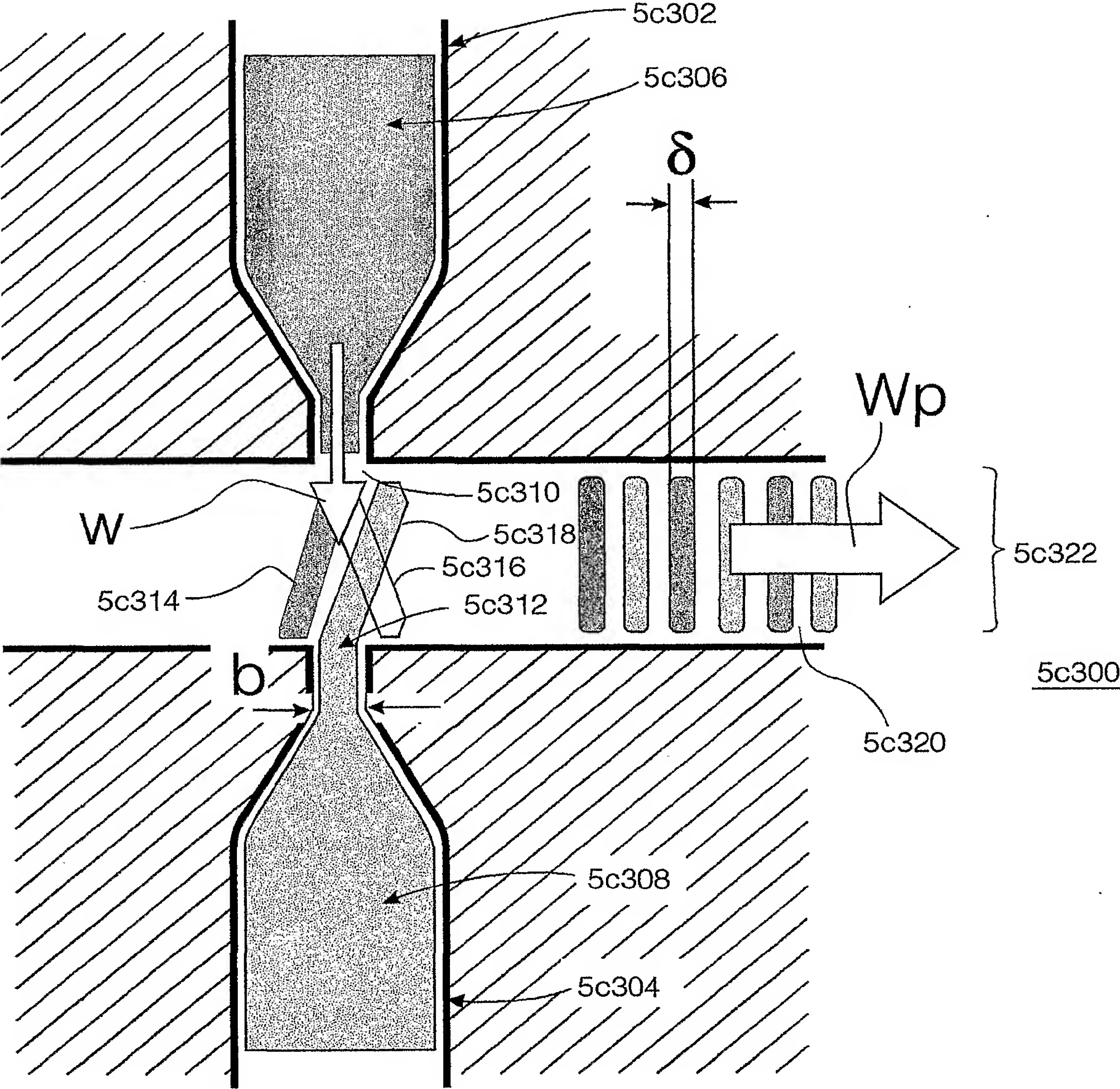


Fig. 5c

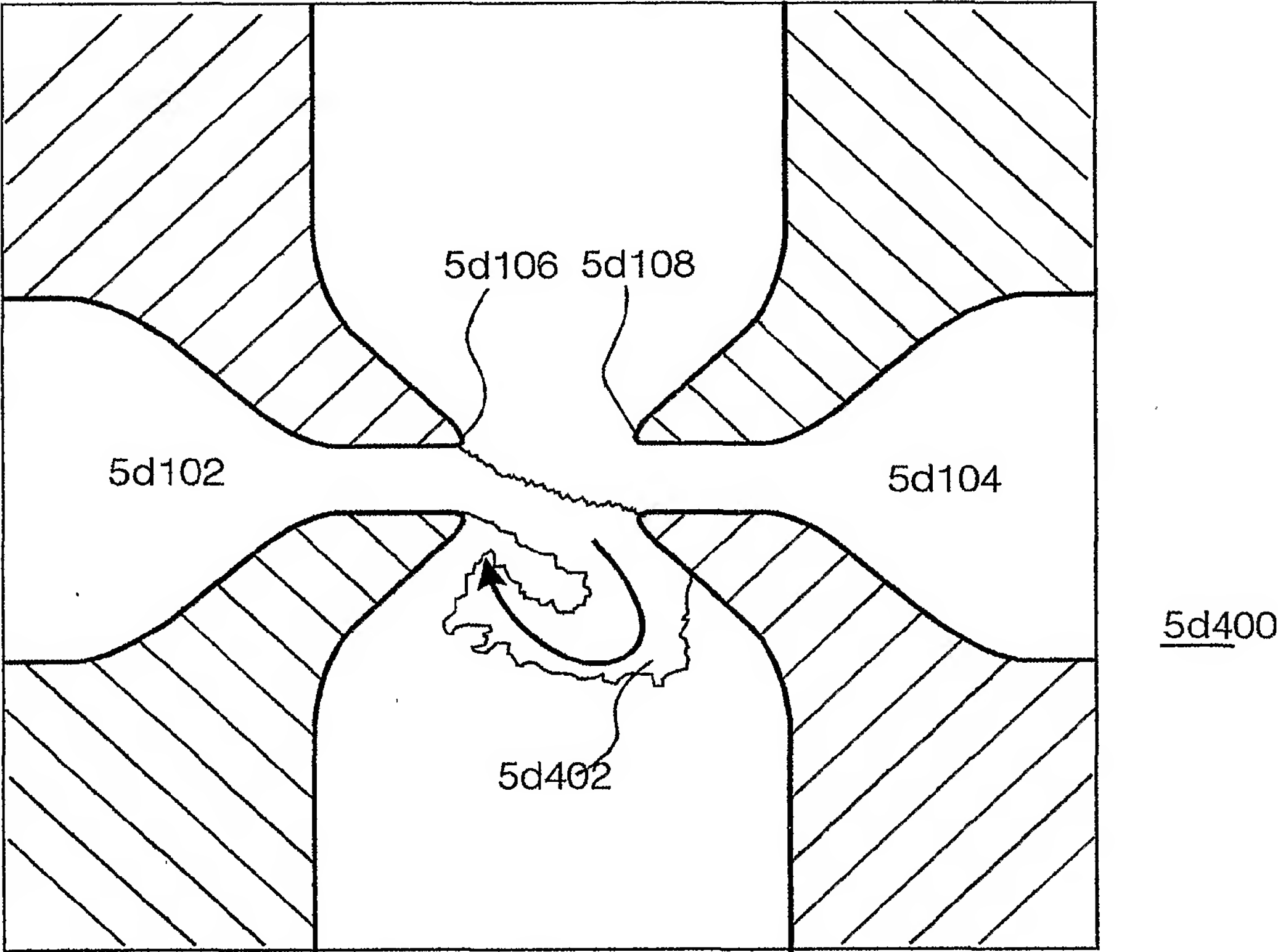


Fig. 5d

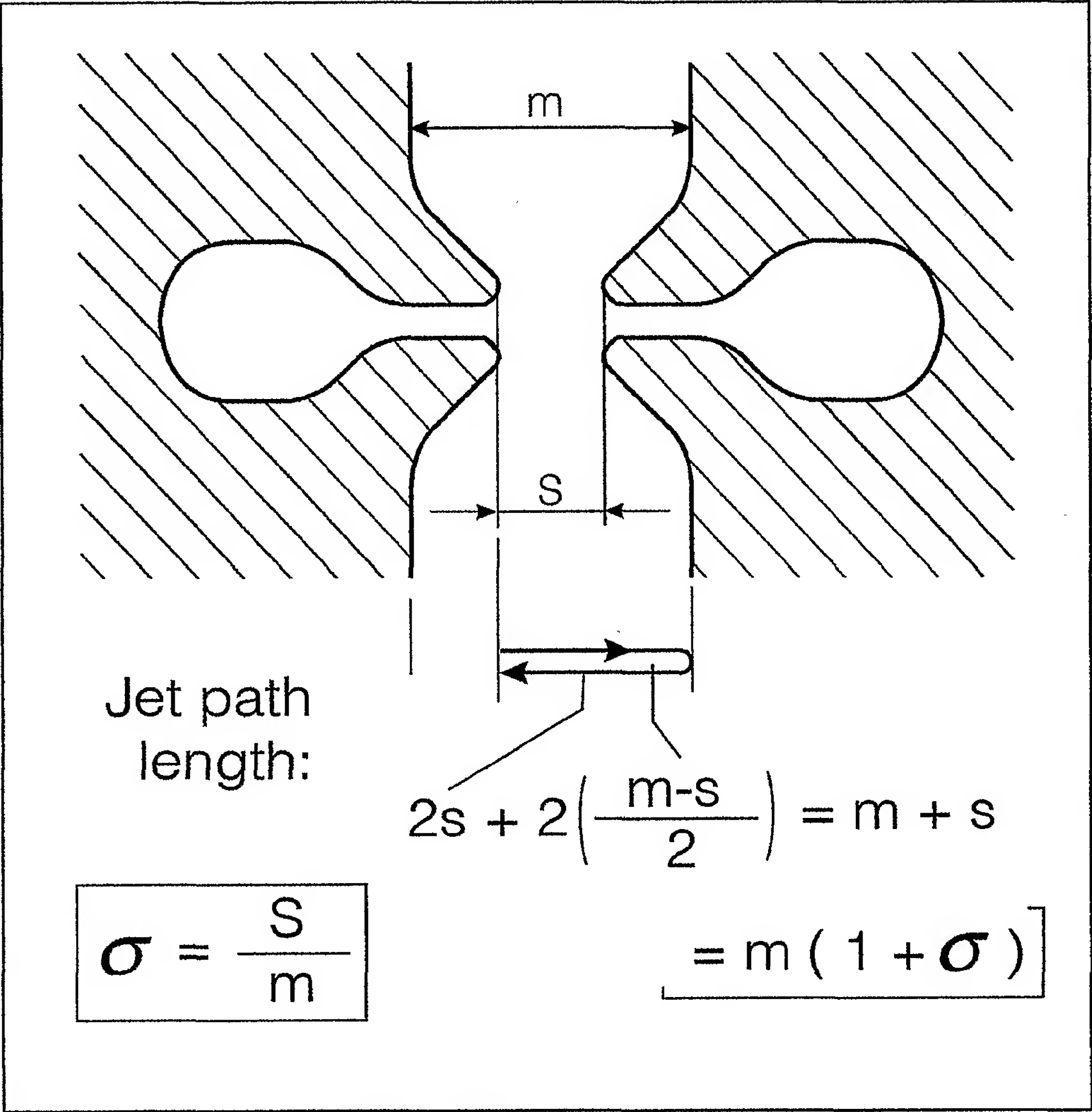


Fig. 5e

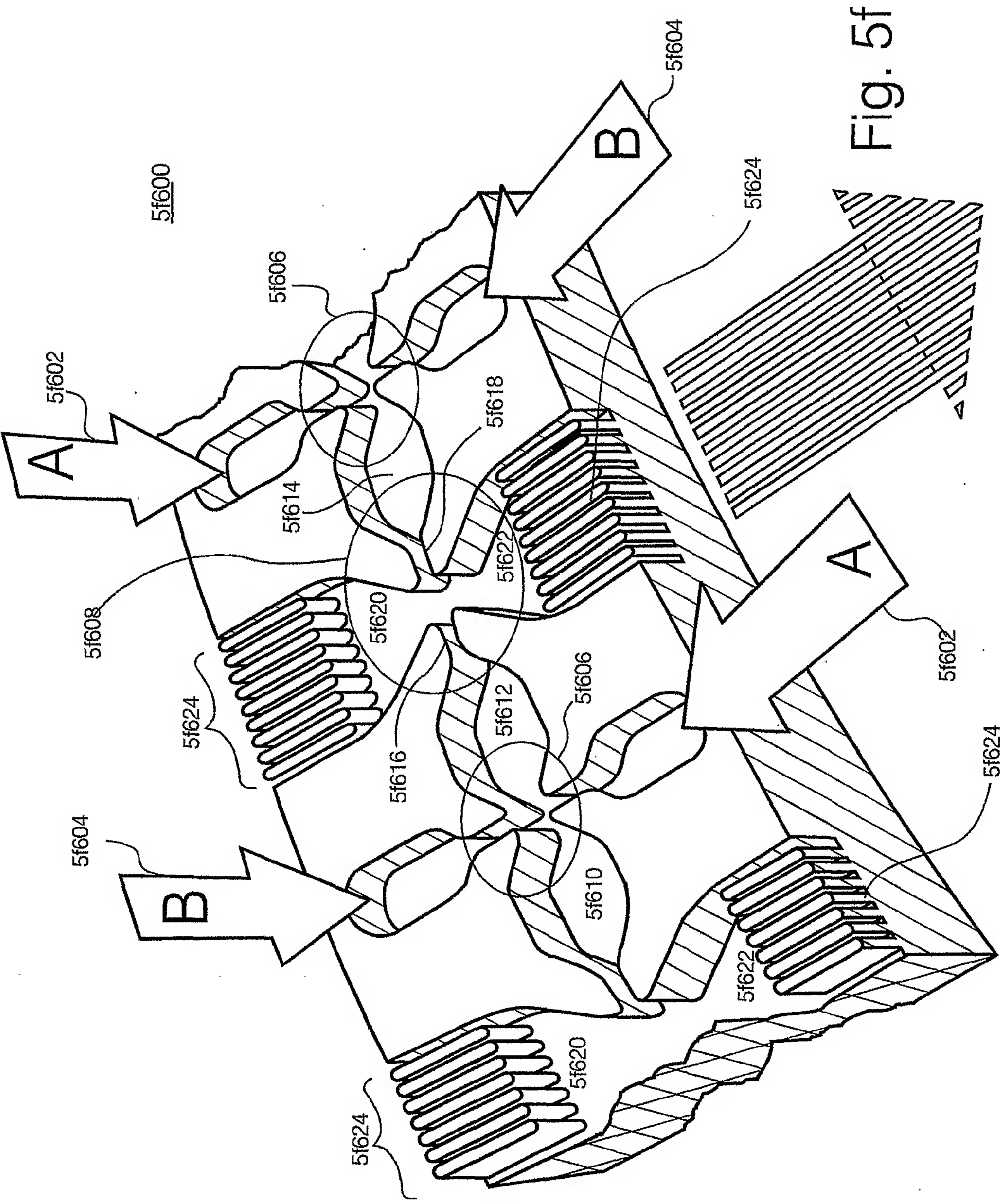


Fig. 5f

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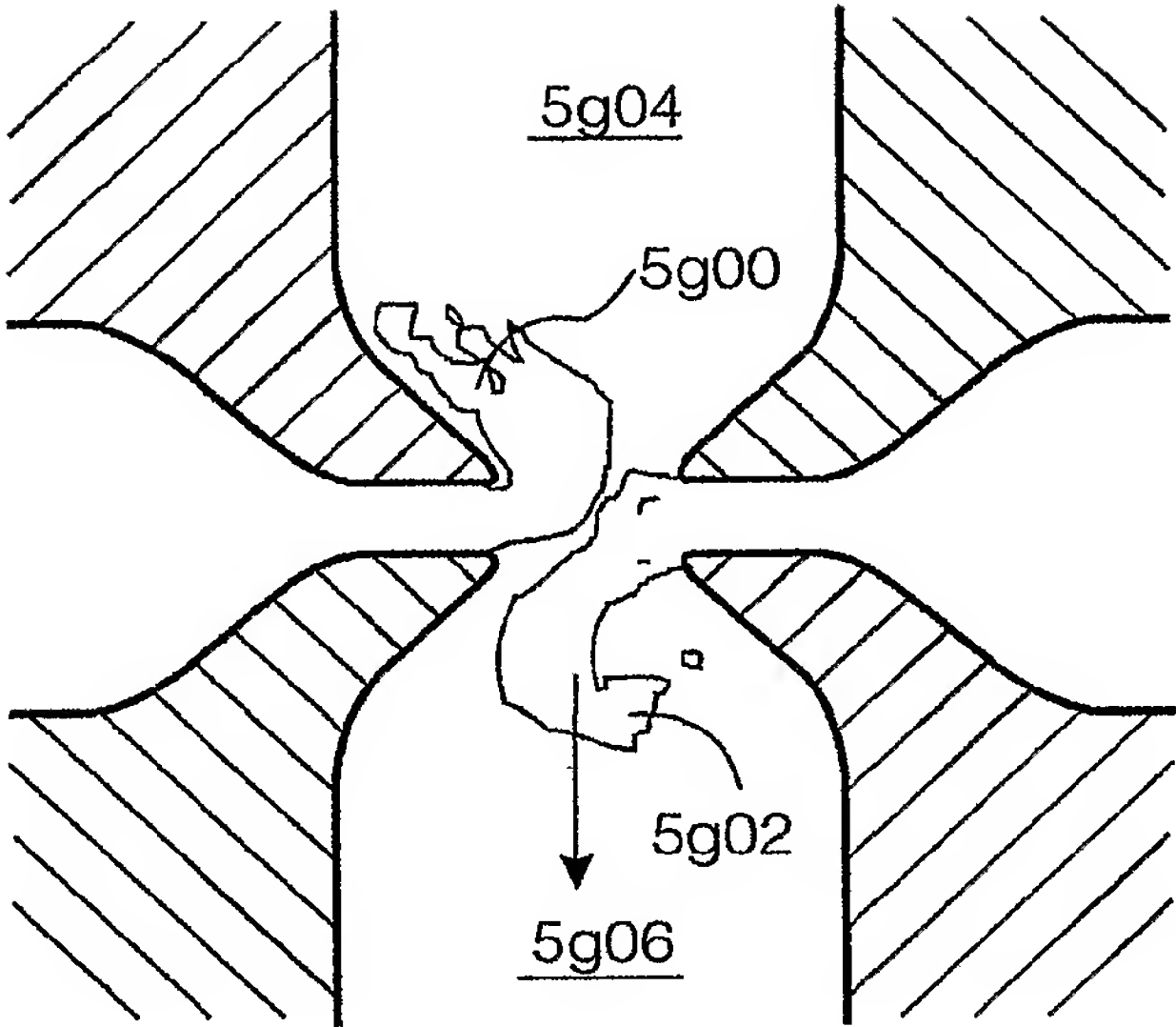


Fig. 5g

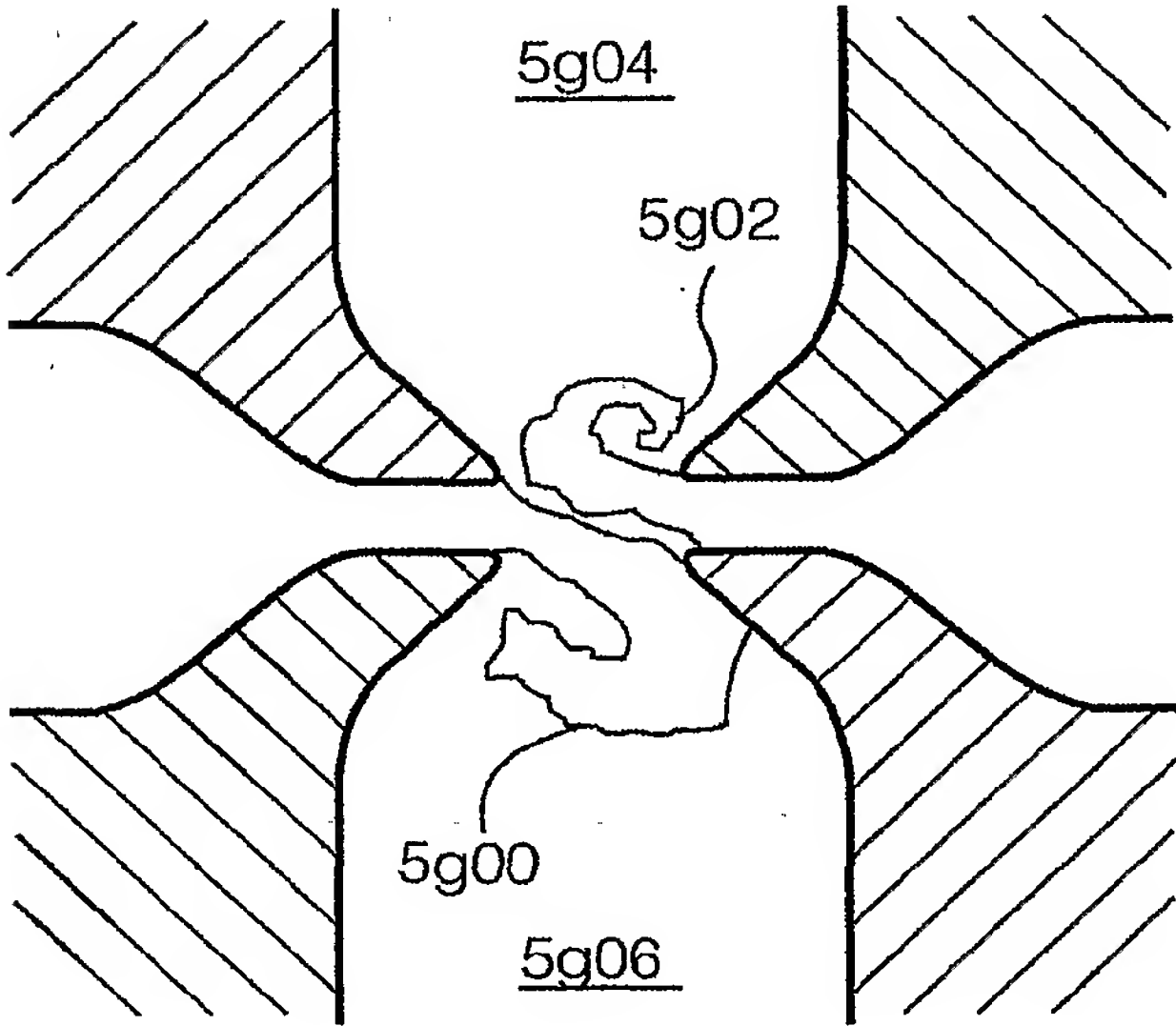


Fig. 5h

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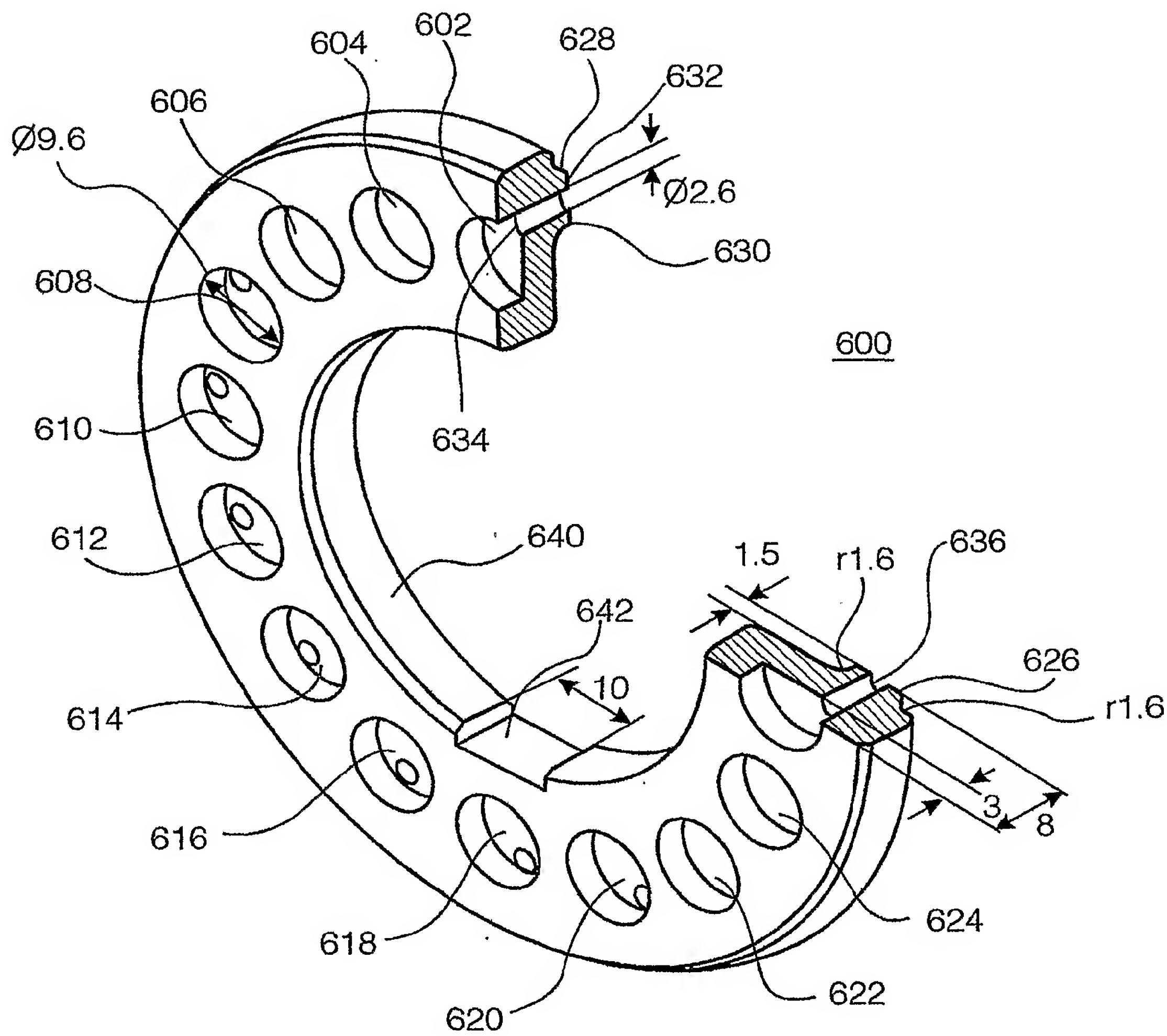


Fig. 6

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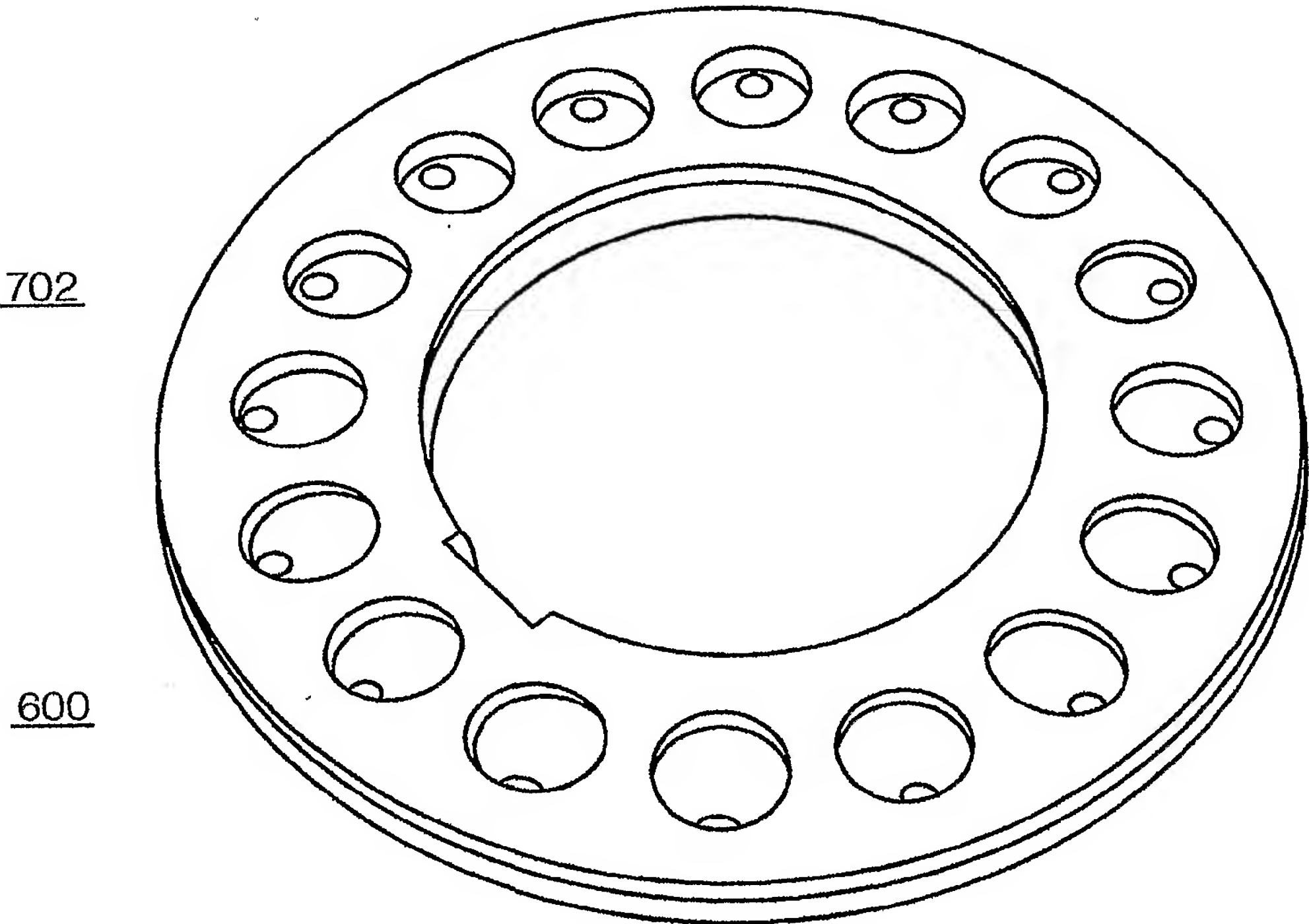


Fig. 7a

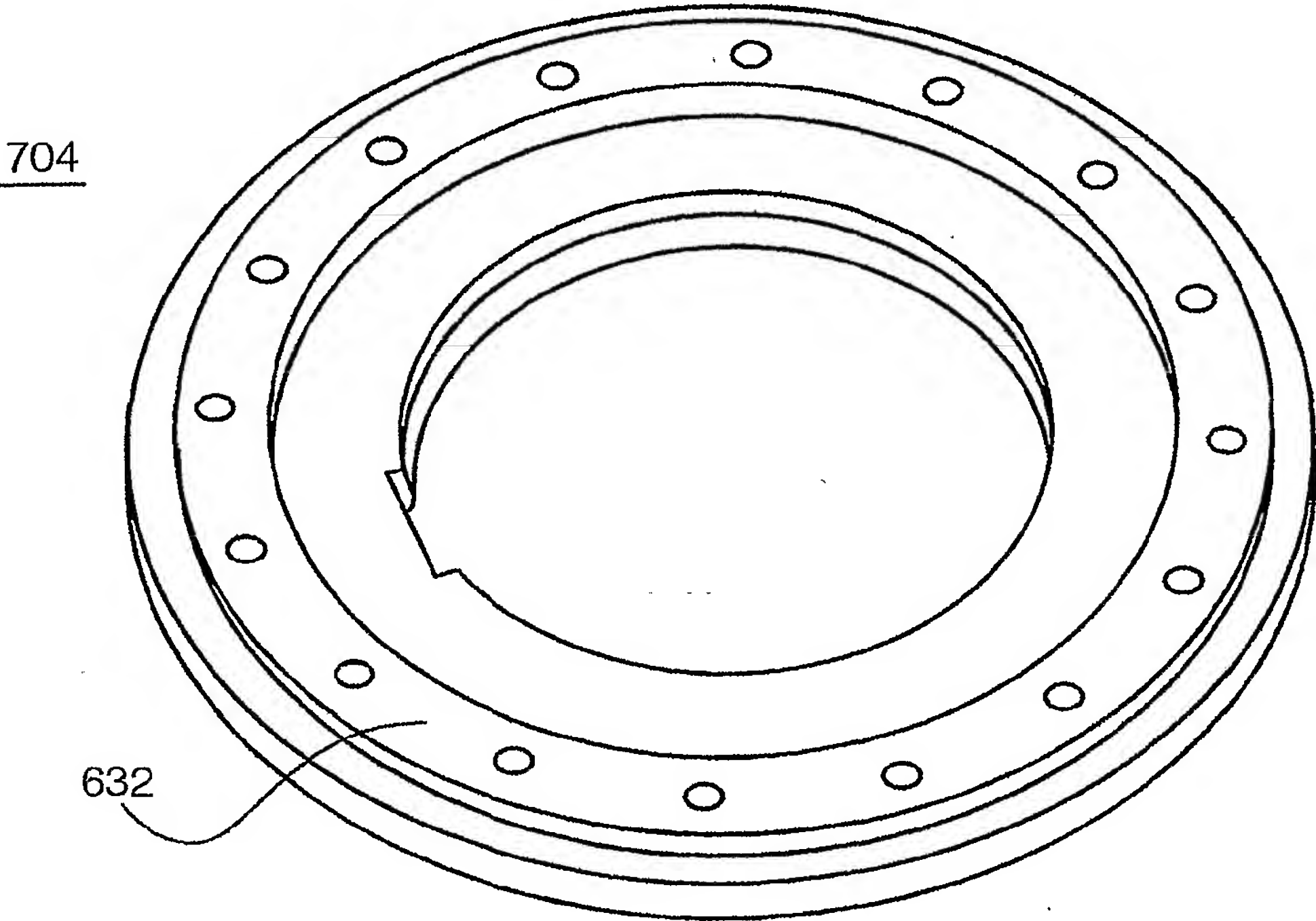


Fig. 7b

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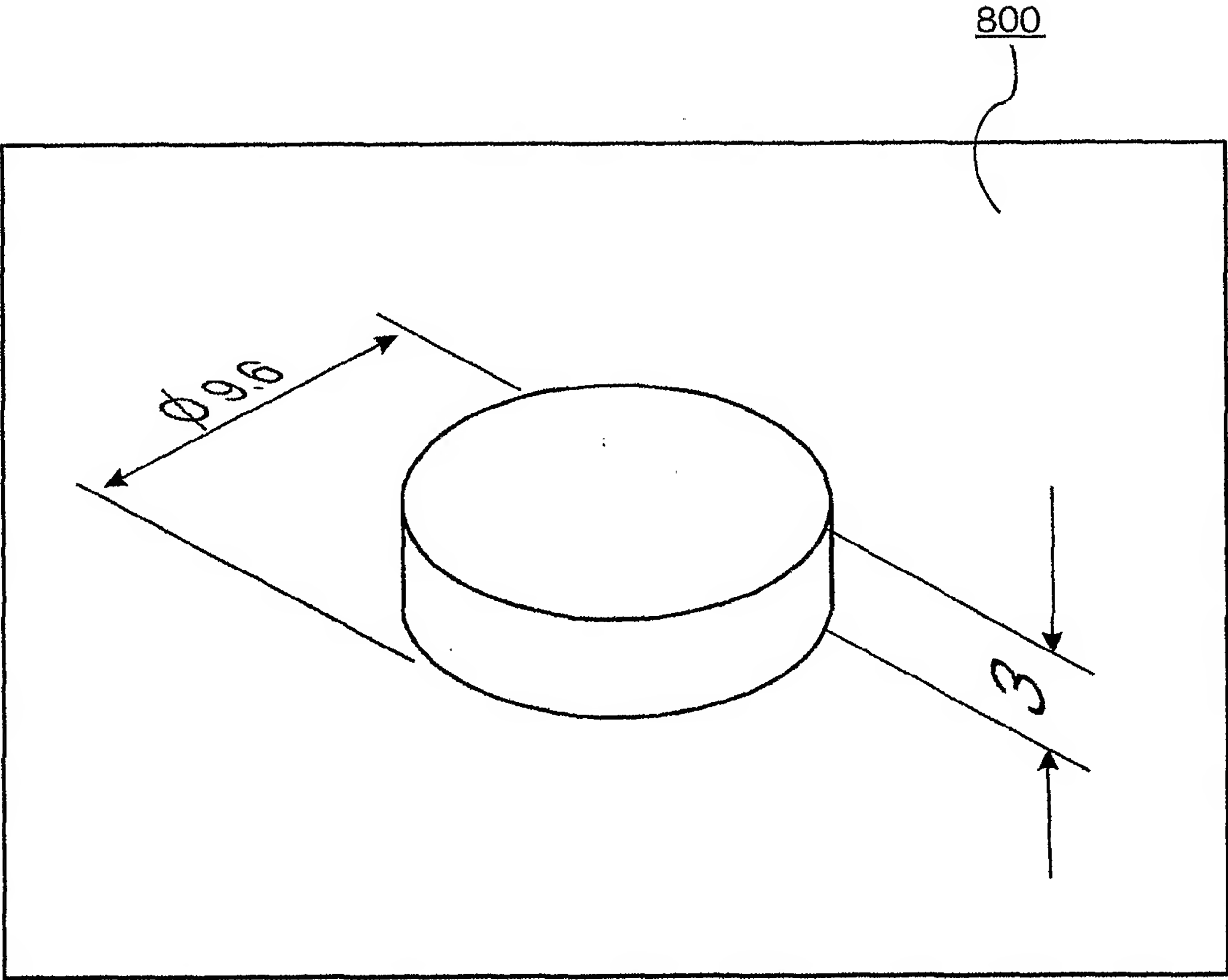


Fig. 8

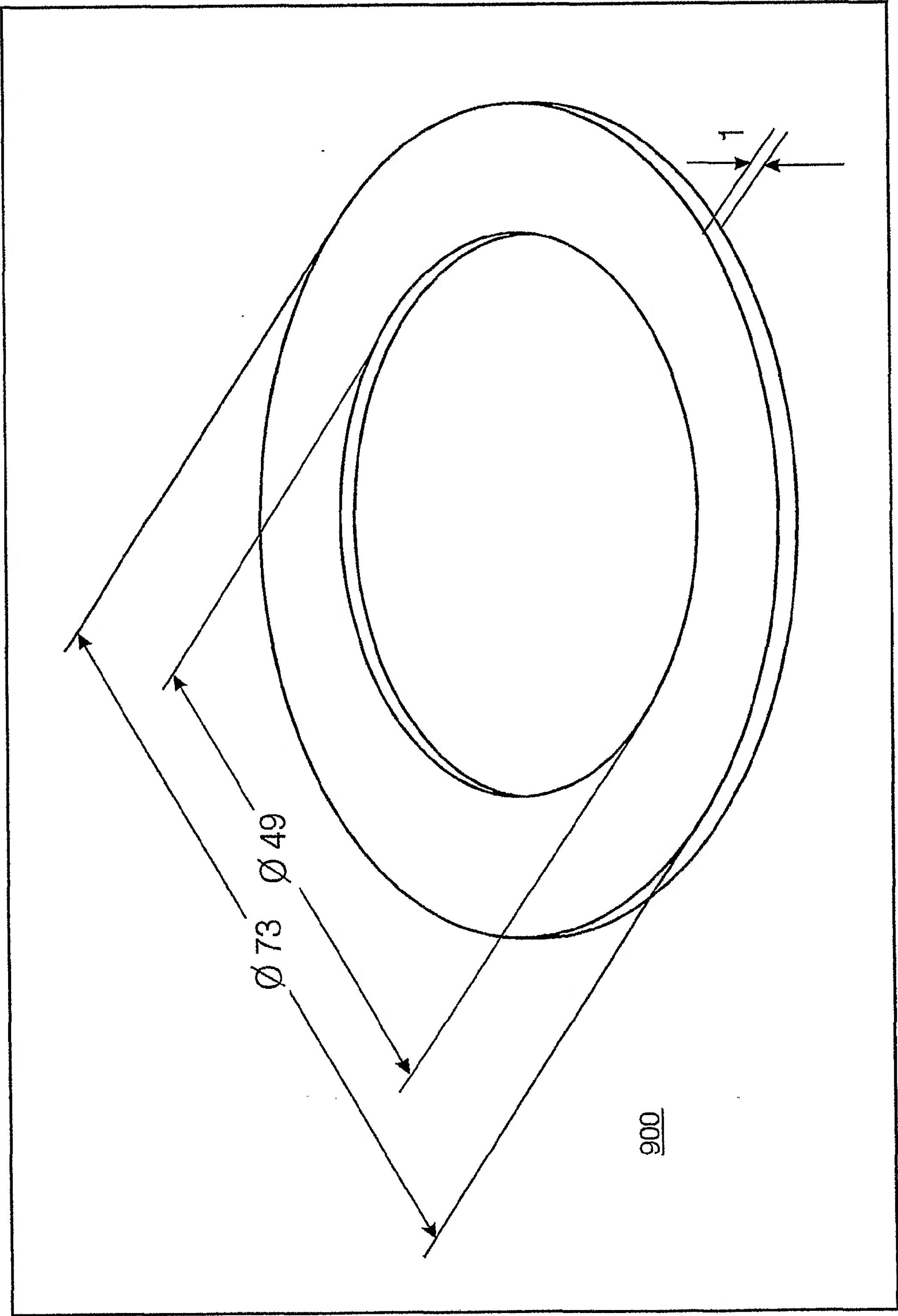


Fig. 9

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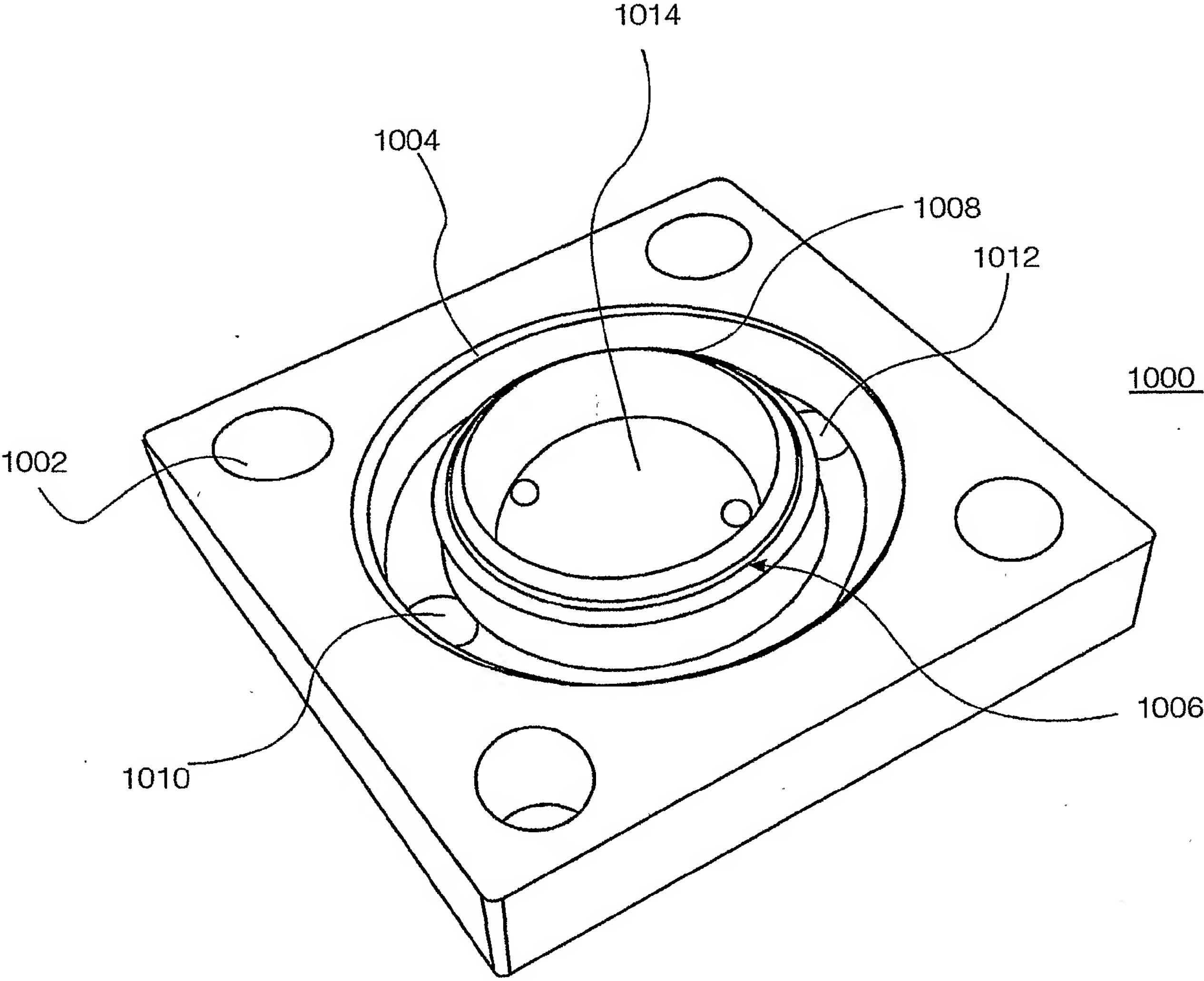


Fig. 10

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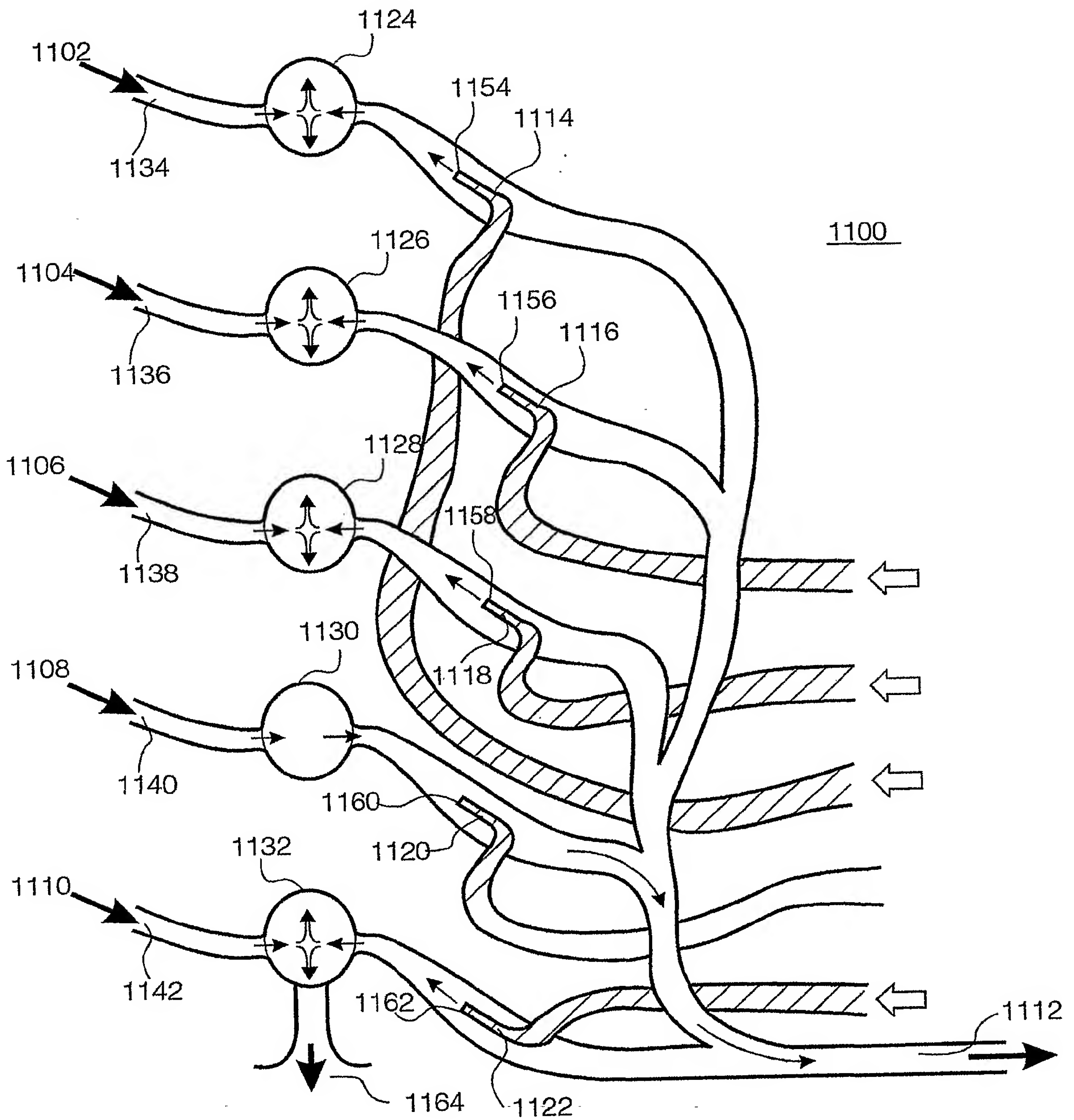
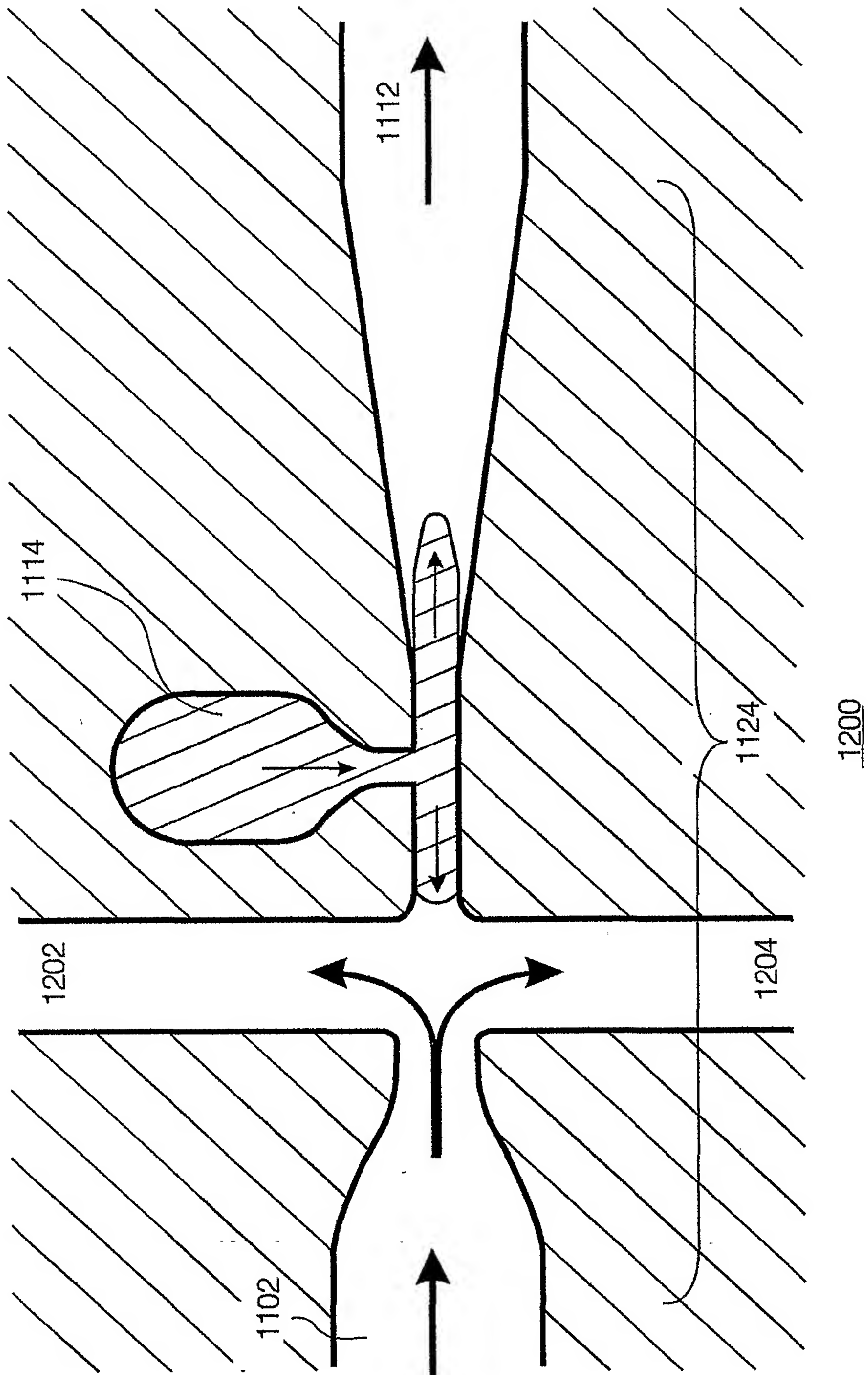


Fig. 11

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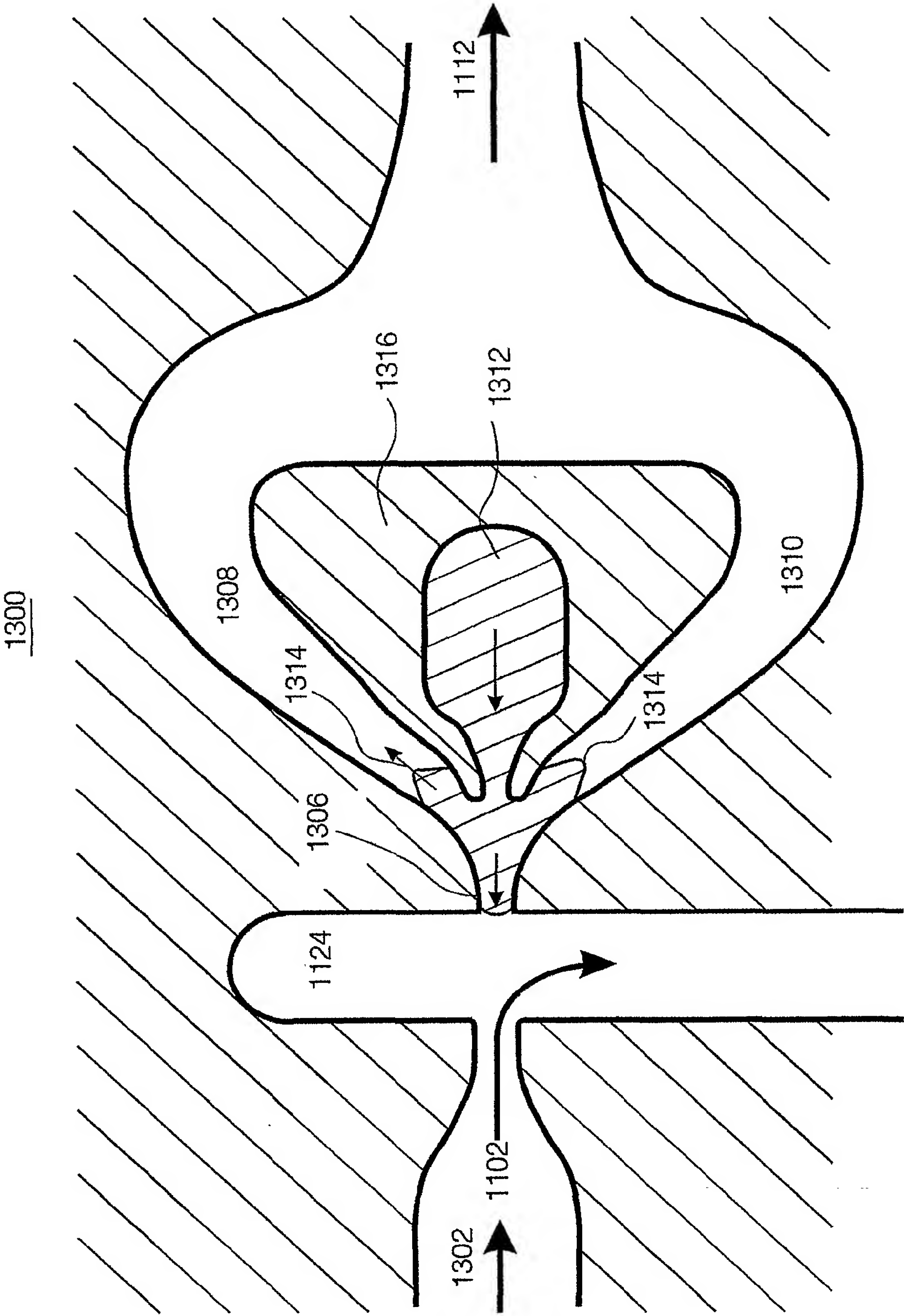


Fig. 13

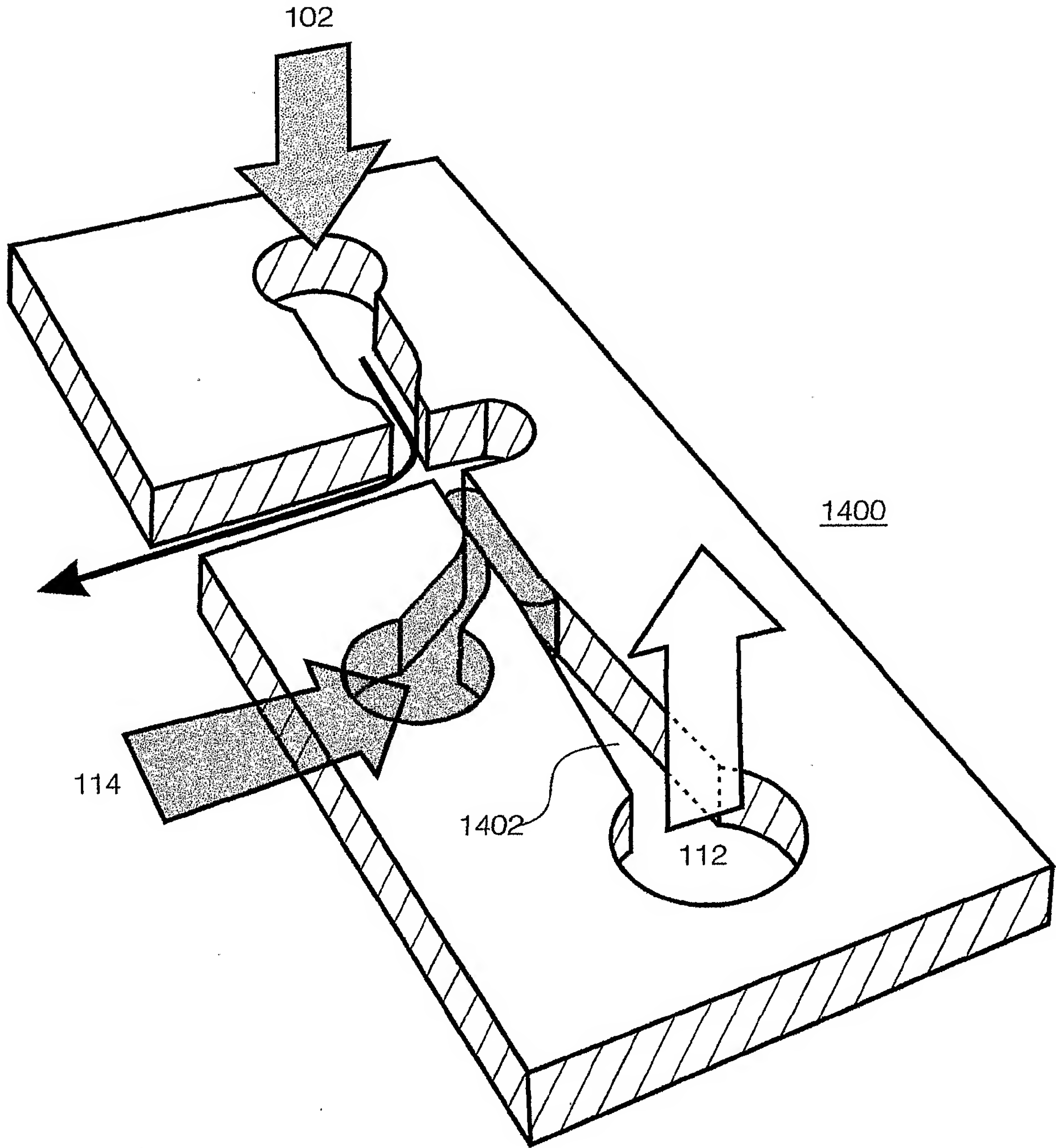


Fig. 14

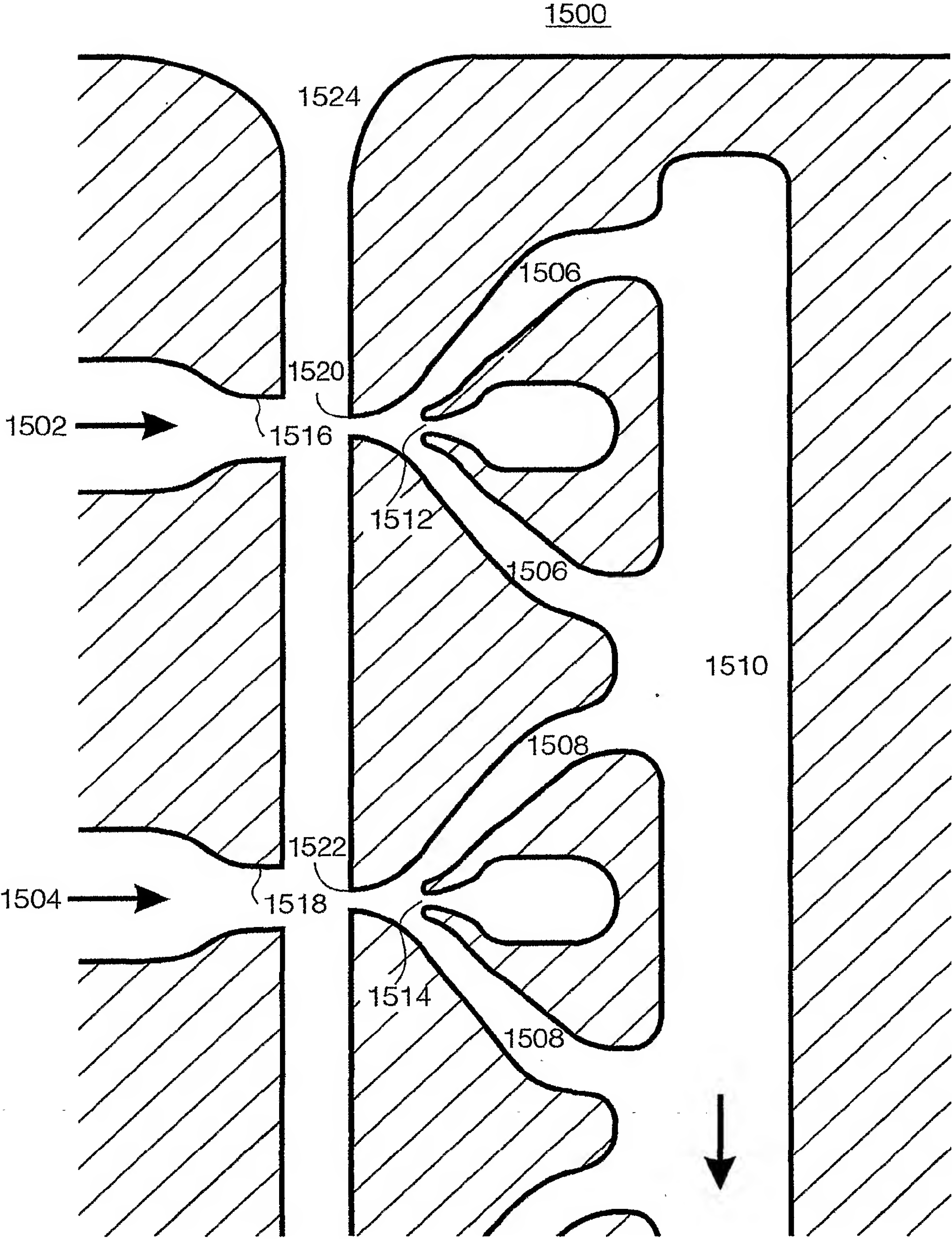


Fig. 15

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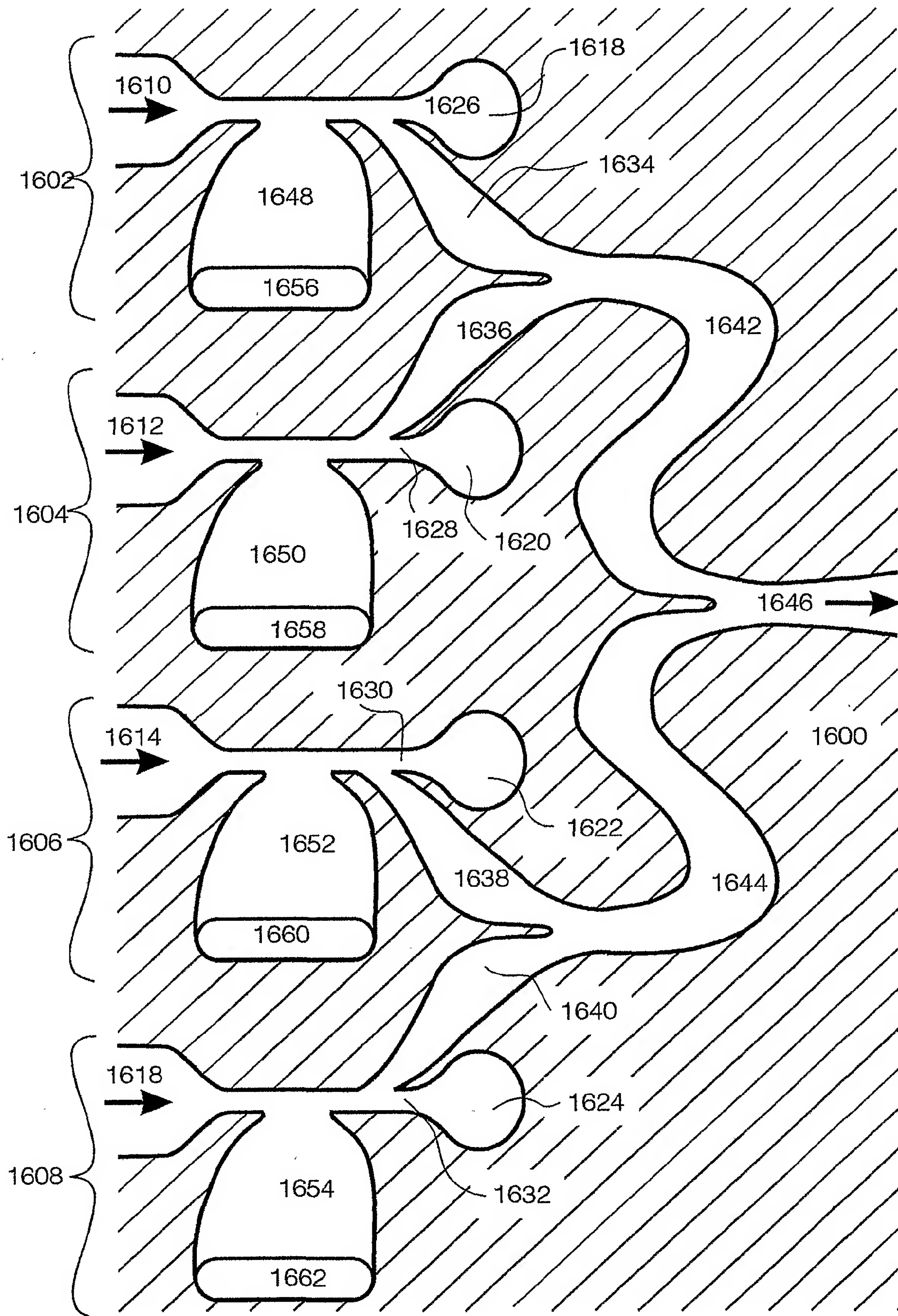


Fig. 16

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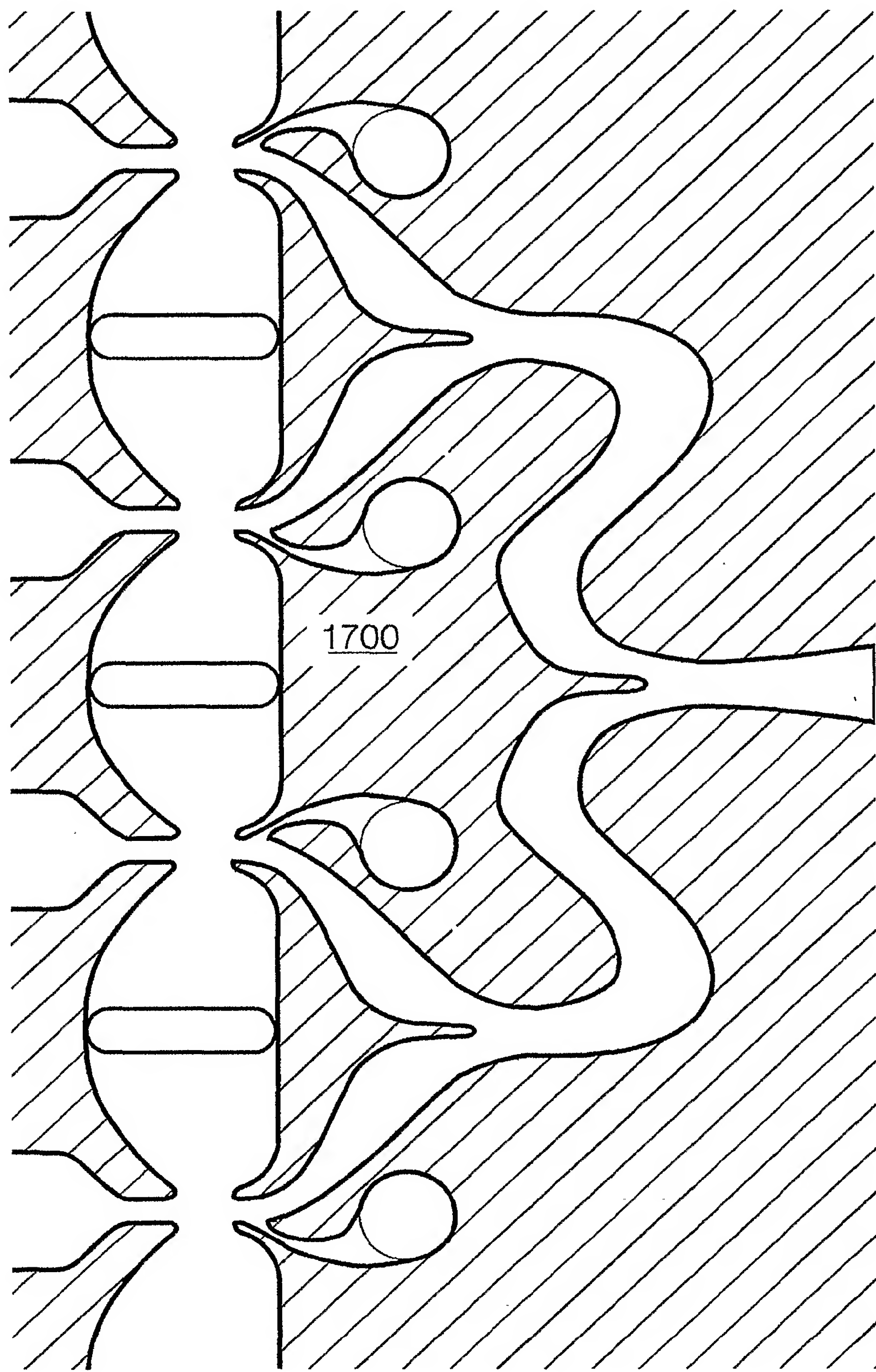


Fig. 17

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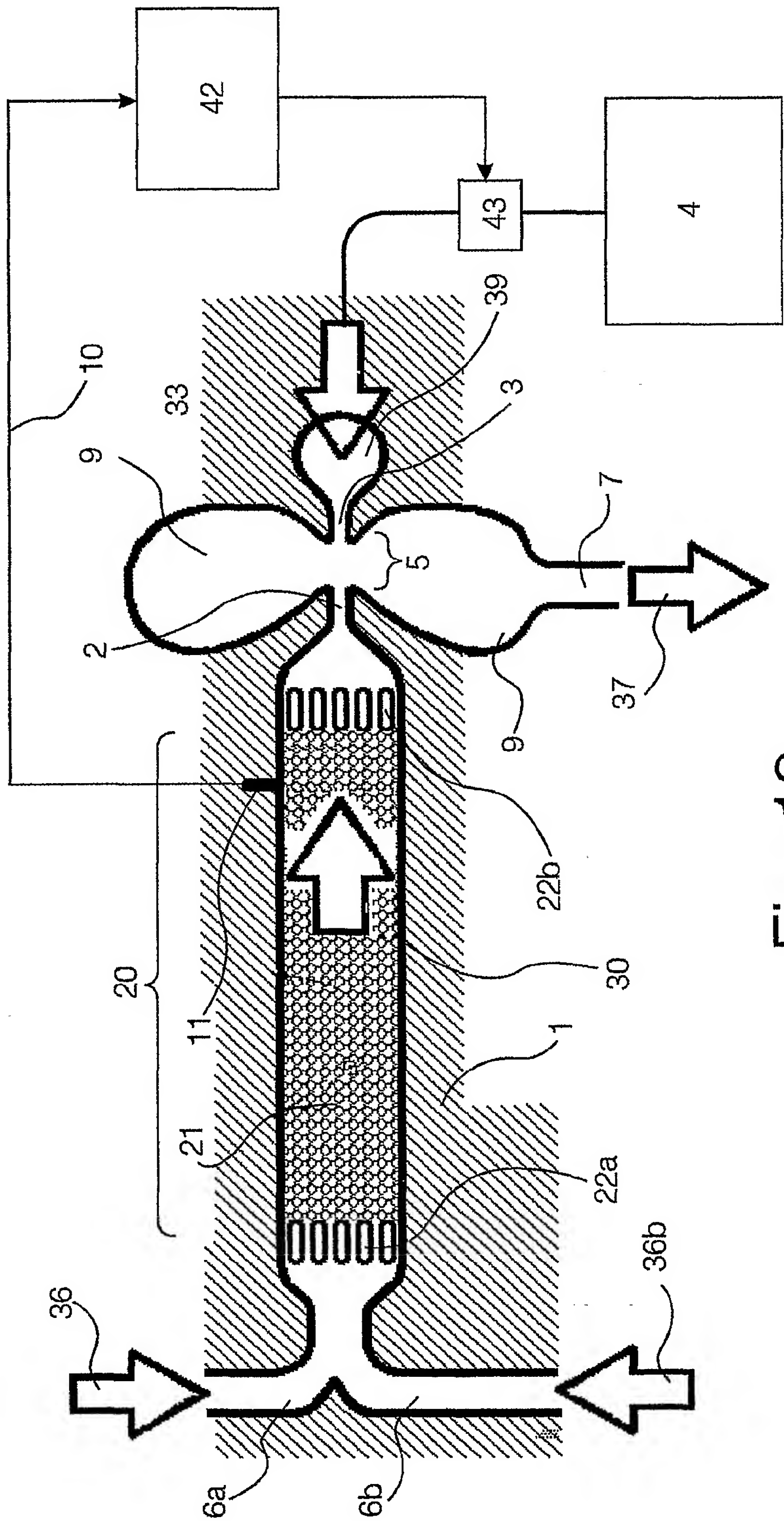


Fig. 18

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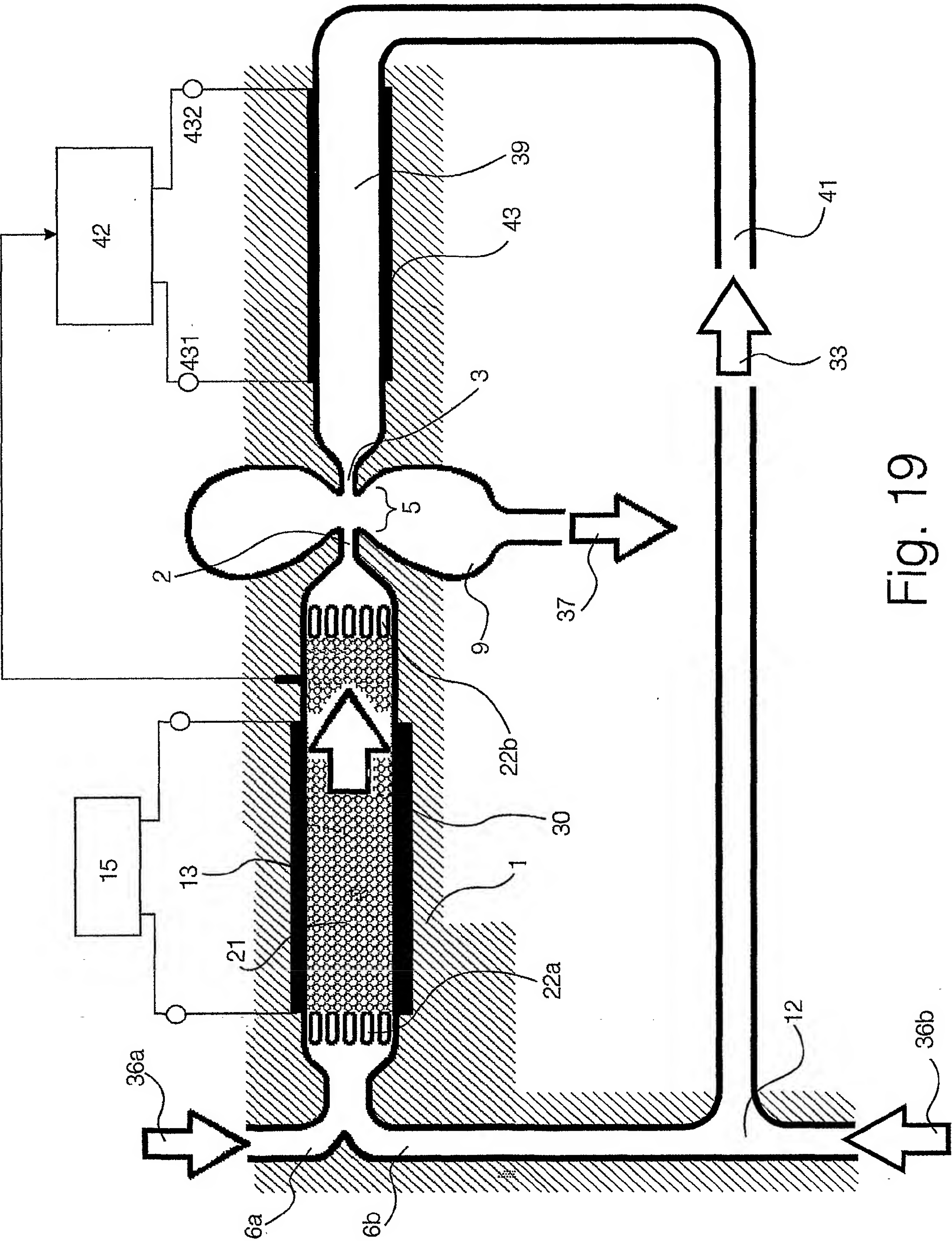
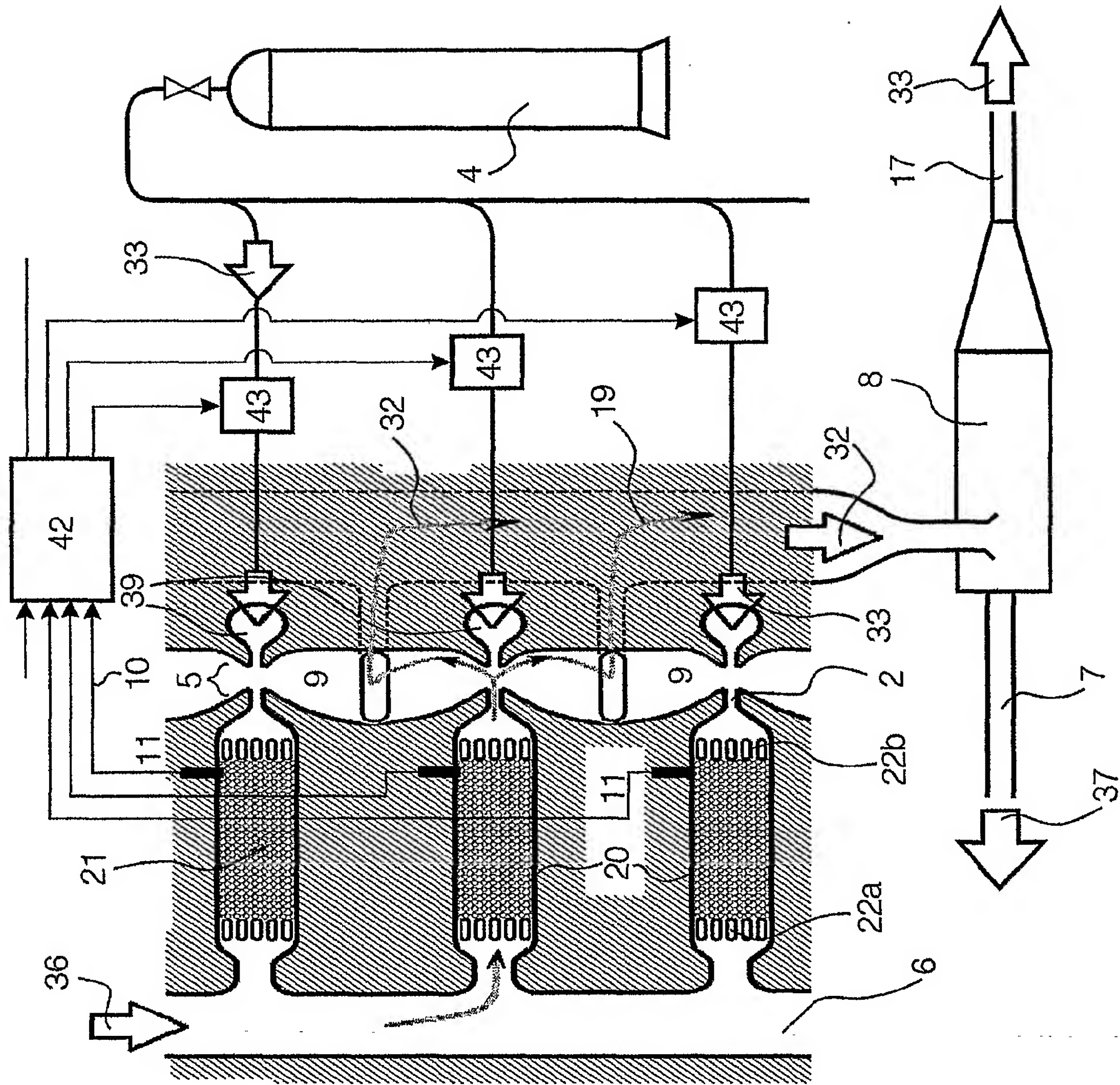


Fig. 19

Fig. 20



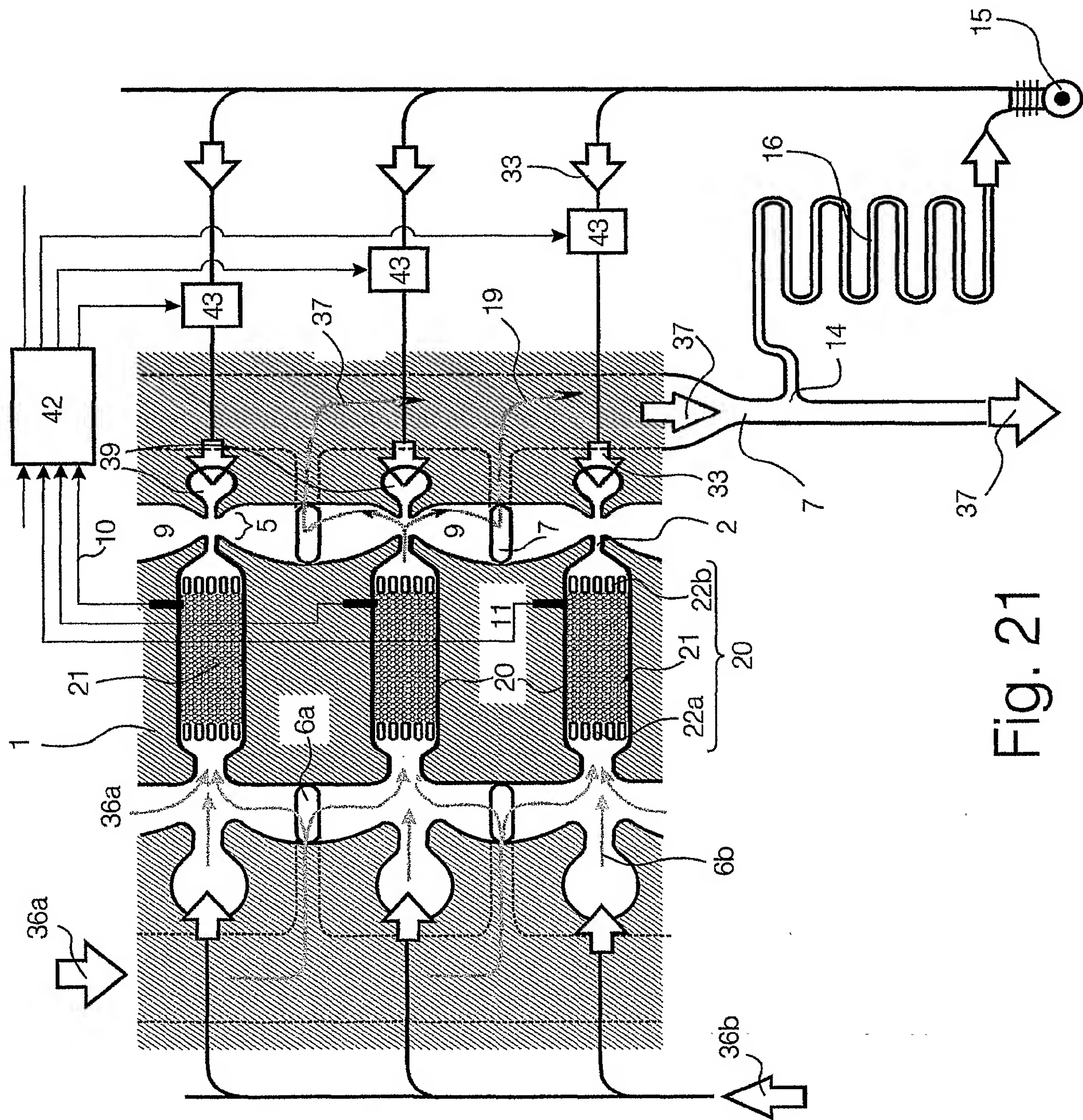


Fig. 21

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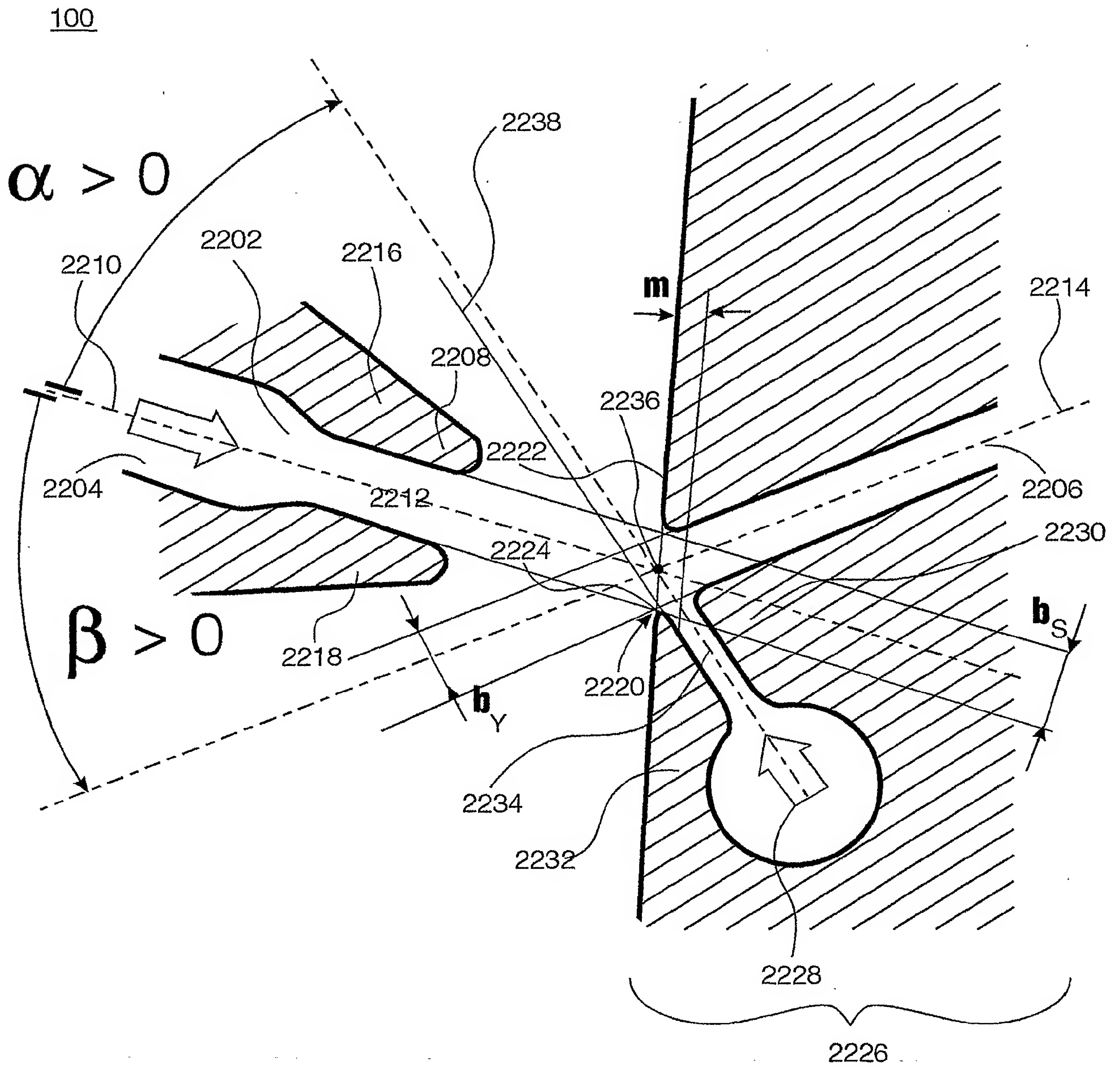


Fig. 22

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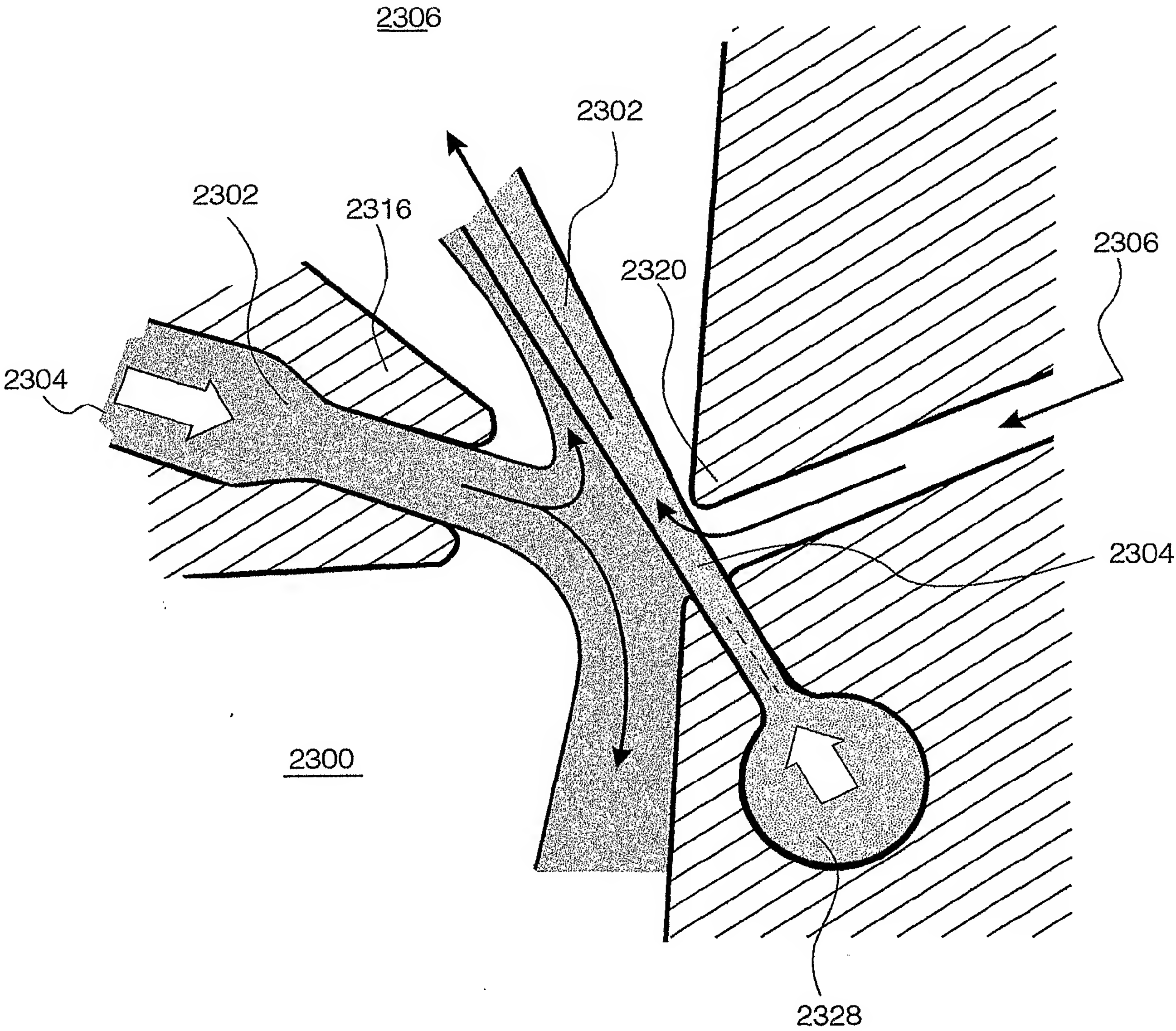


Fig. 23

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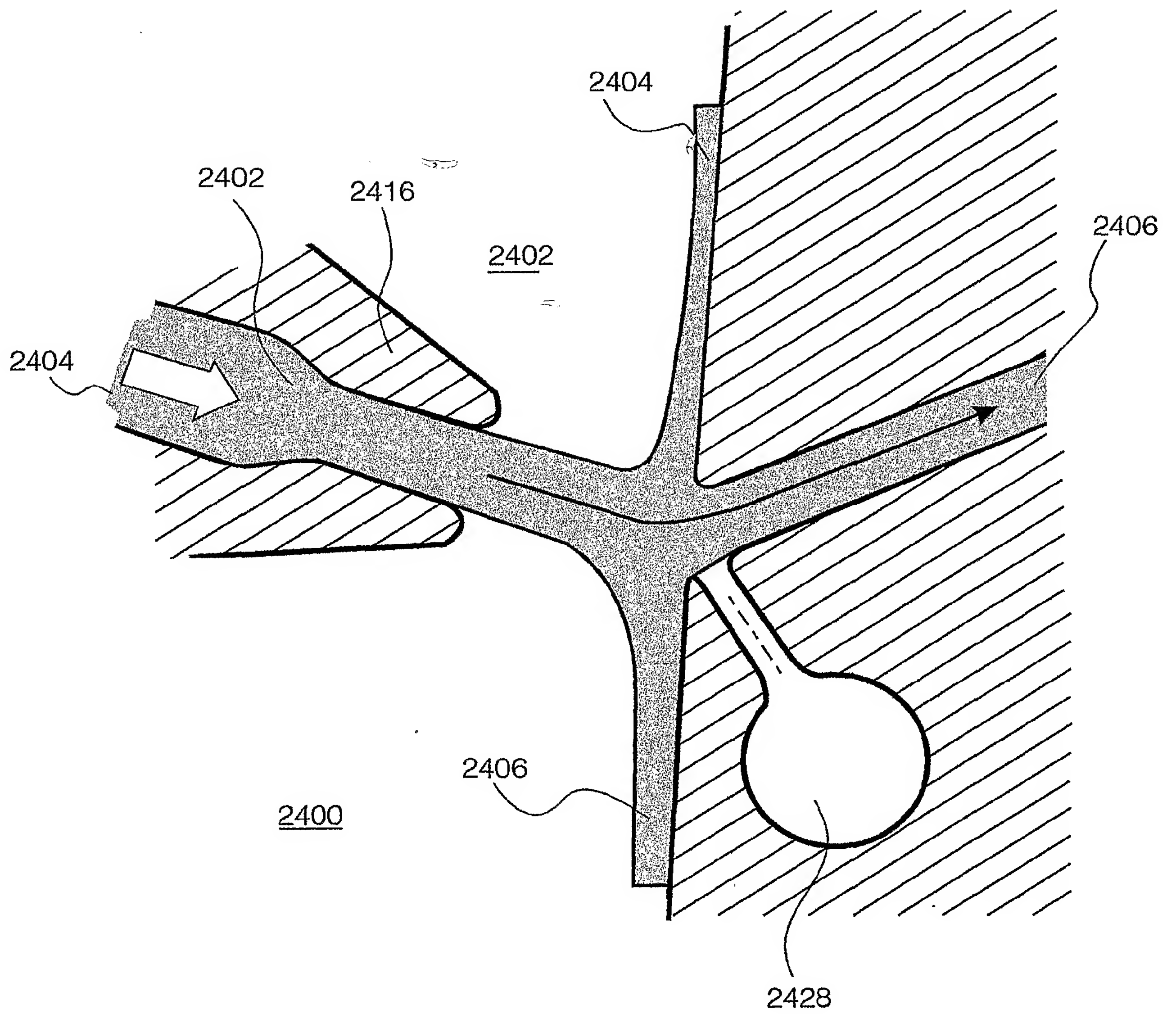


Fig. 24

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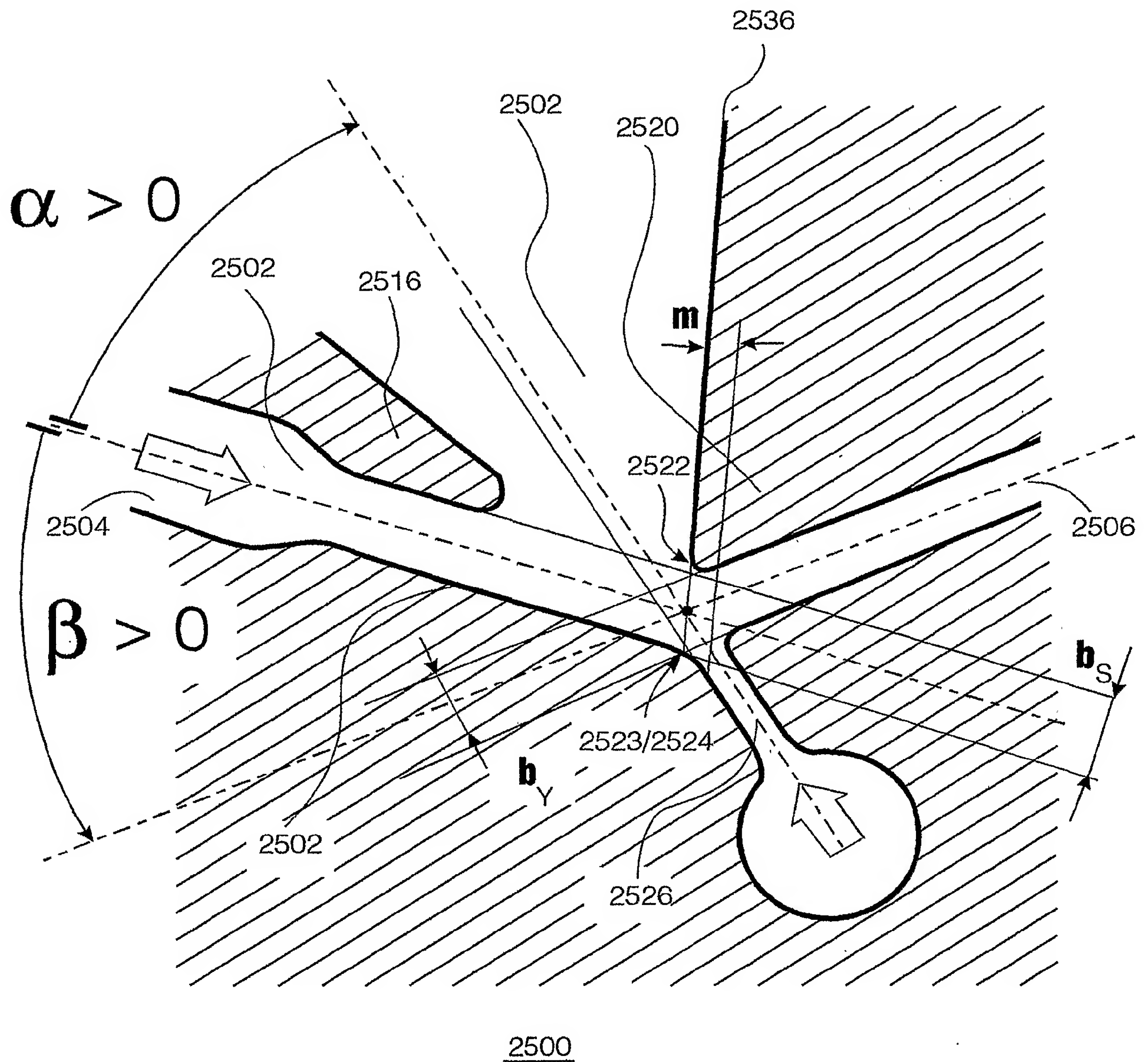


Fig. 25

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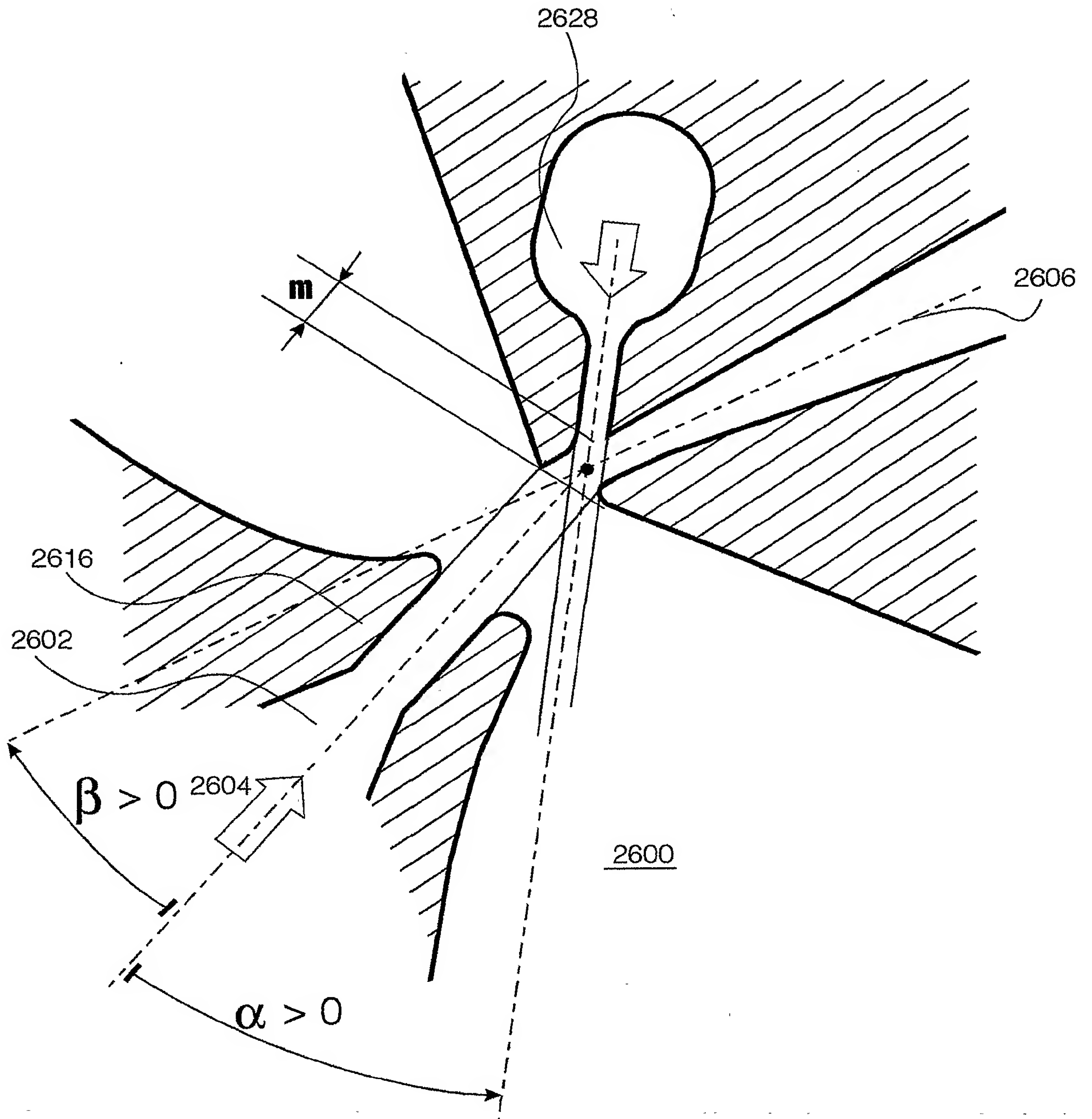


Fig. 26

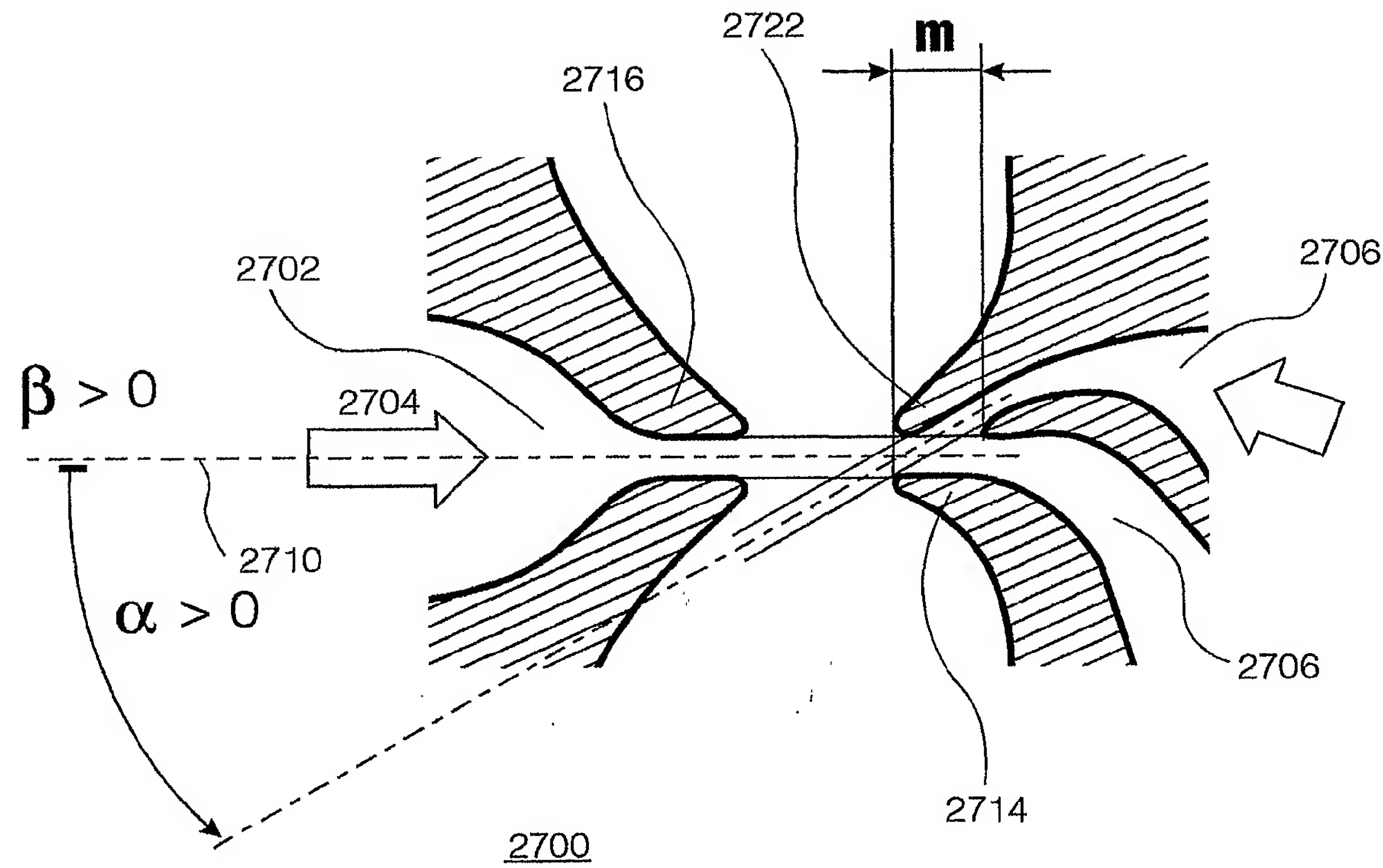


Fig. 27

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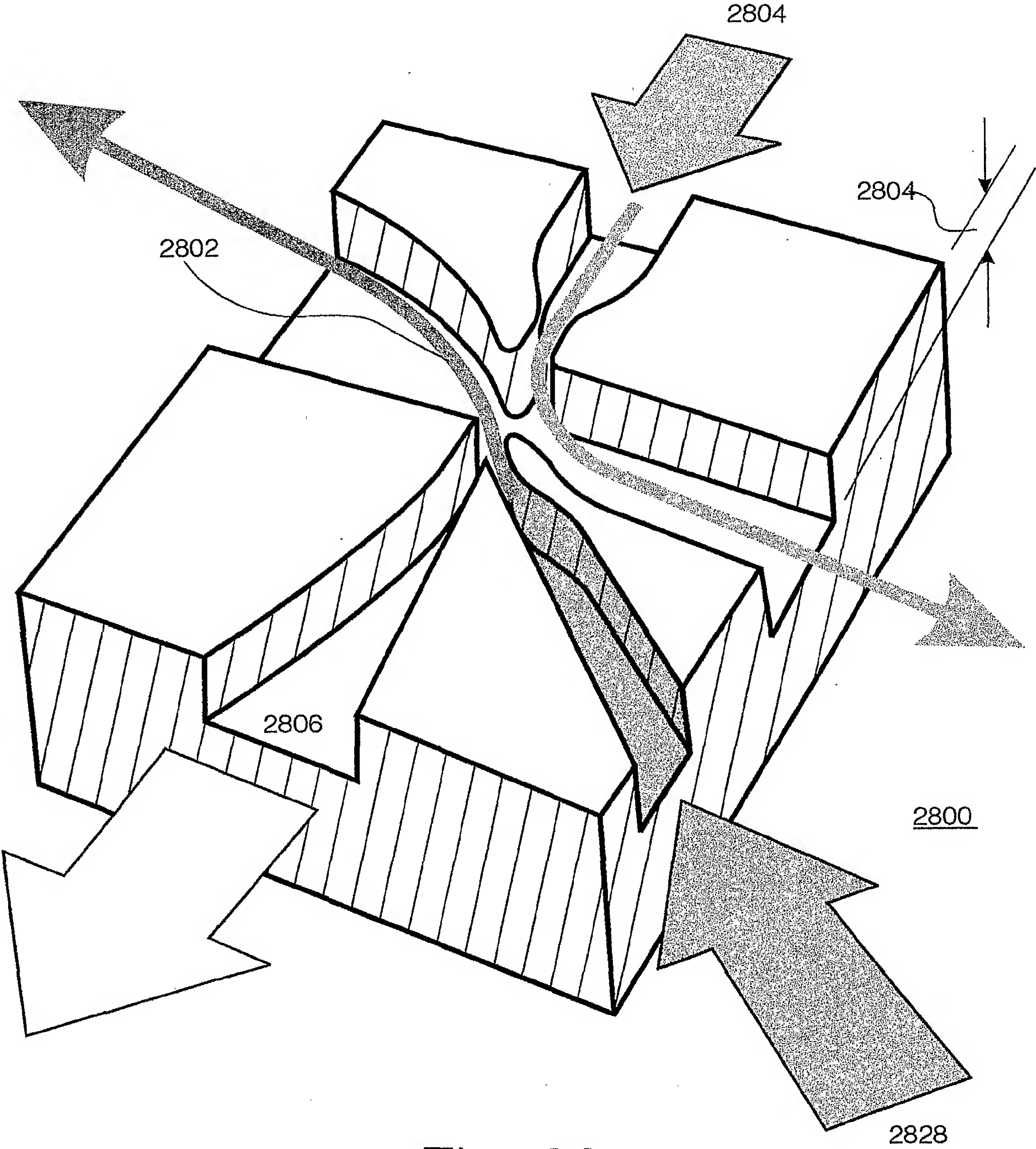


Fig. 28

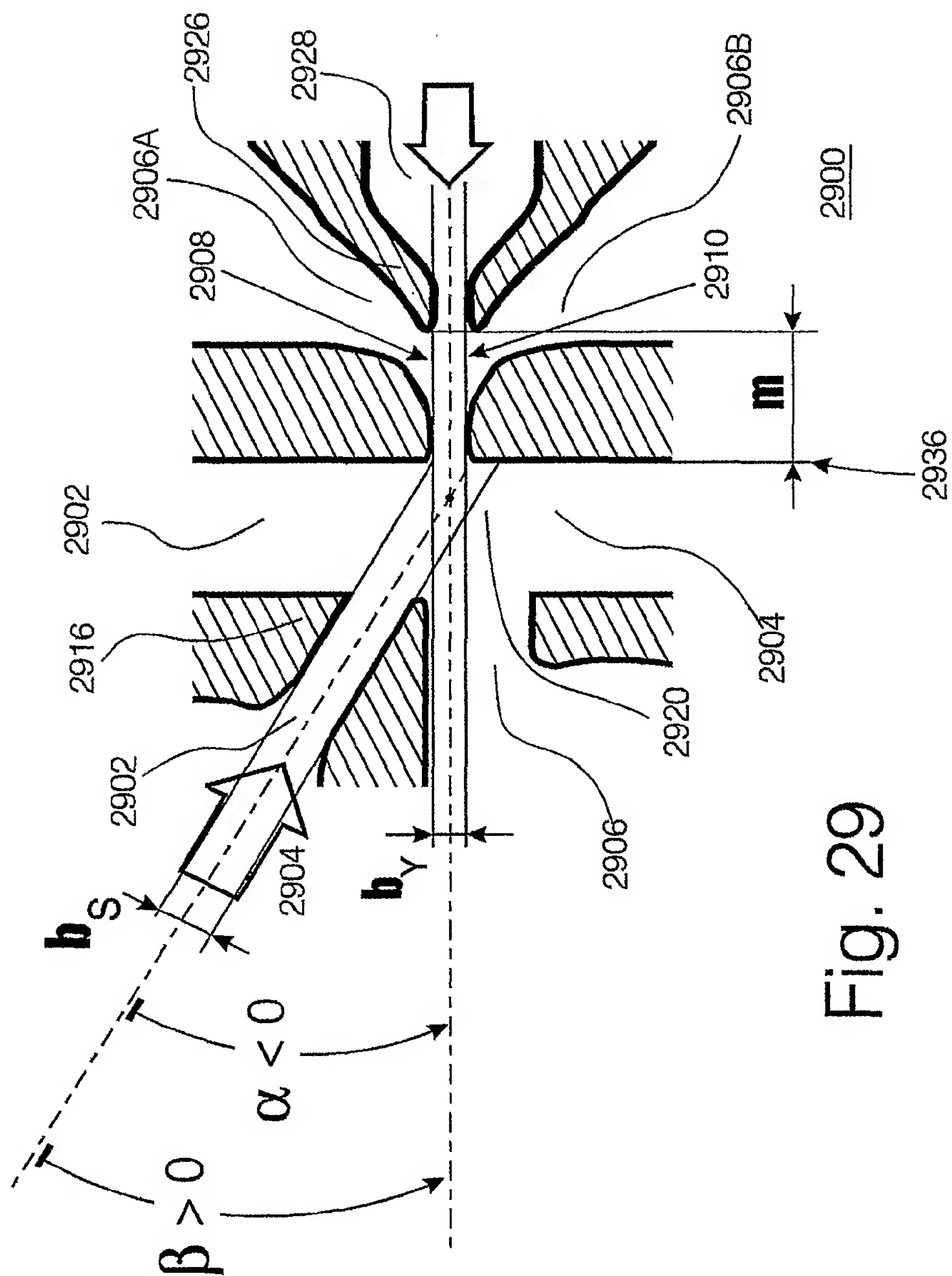


Fig. 29

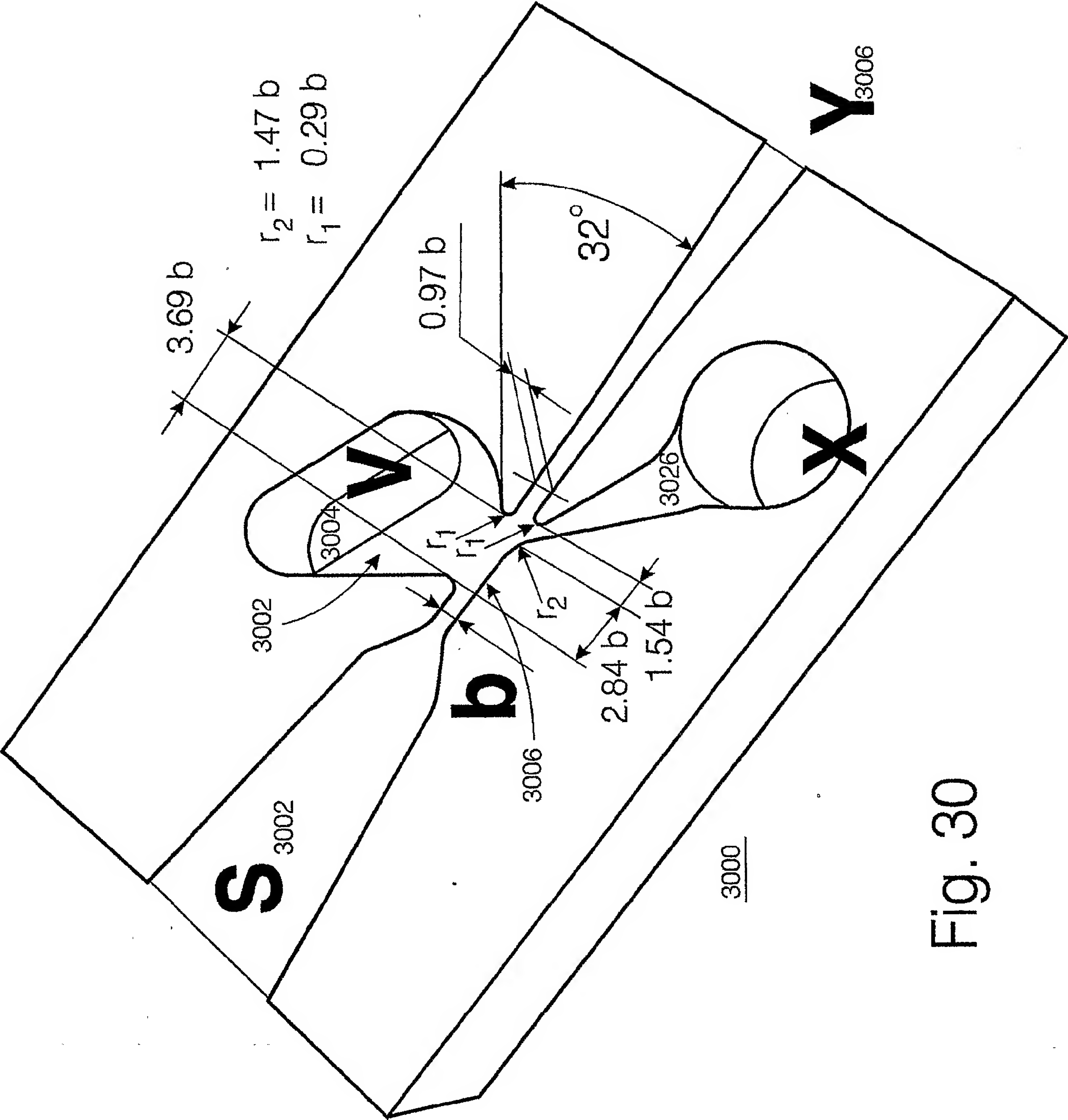


Fig. 30

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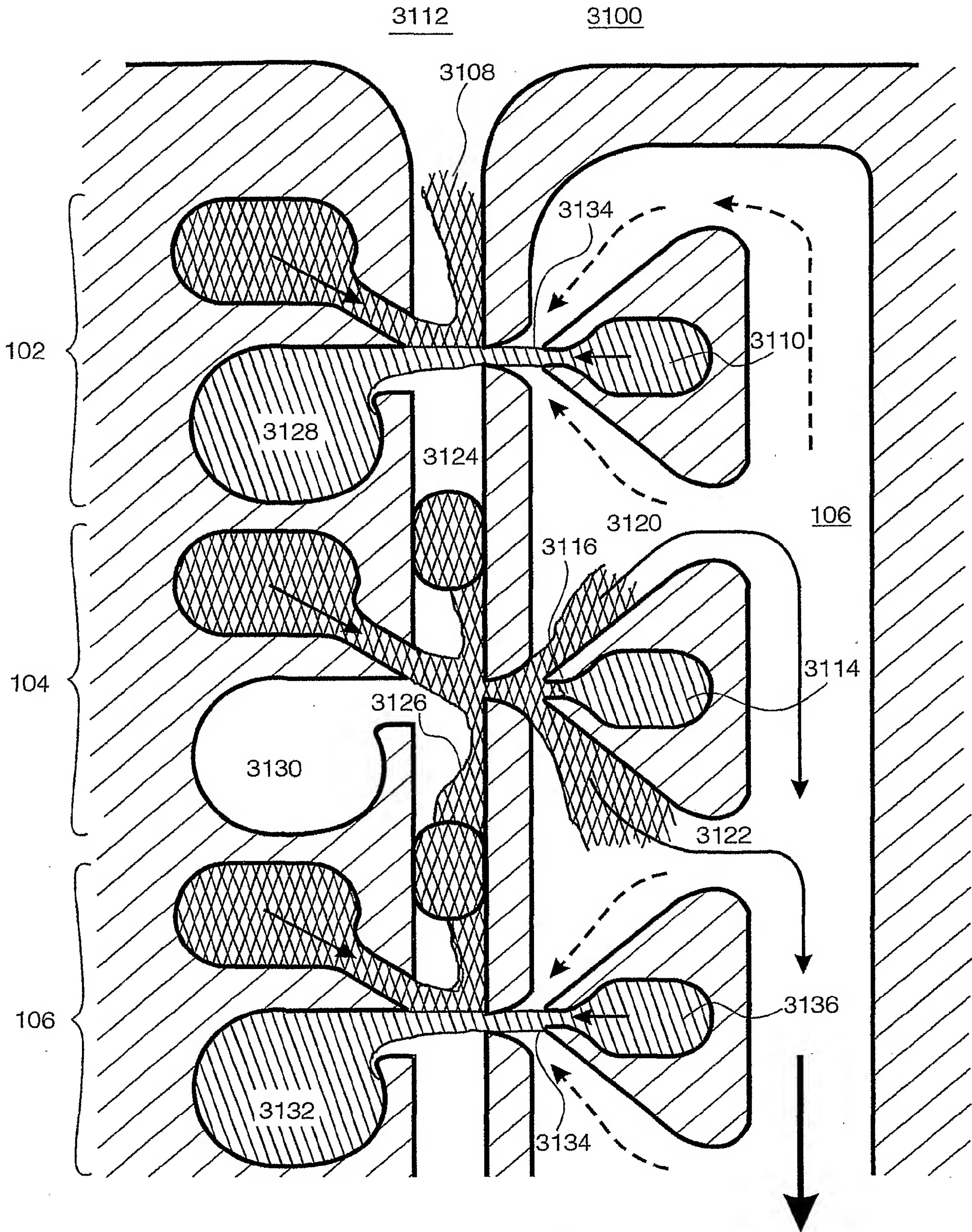


Fig. 31

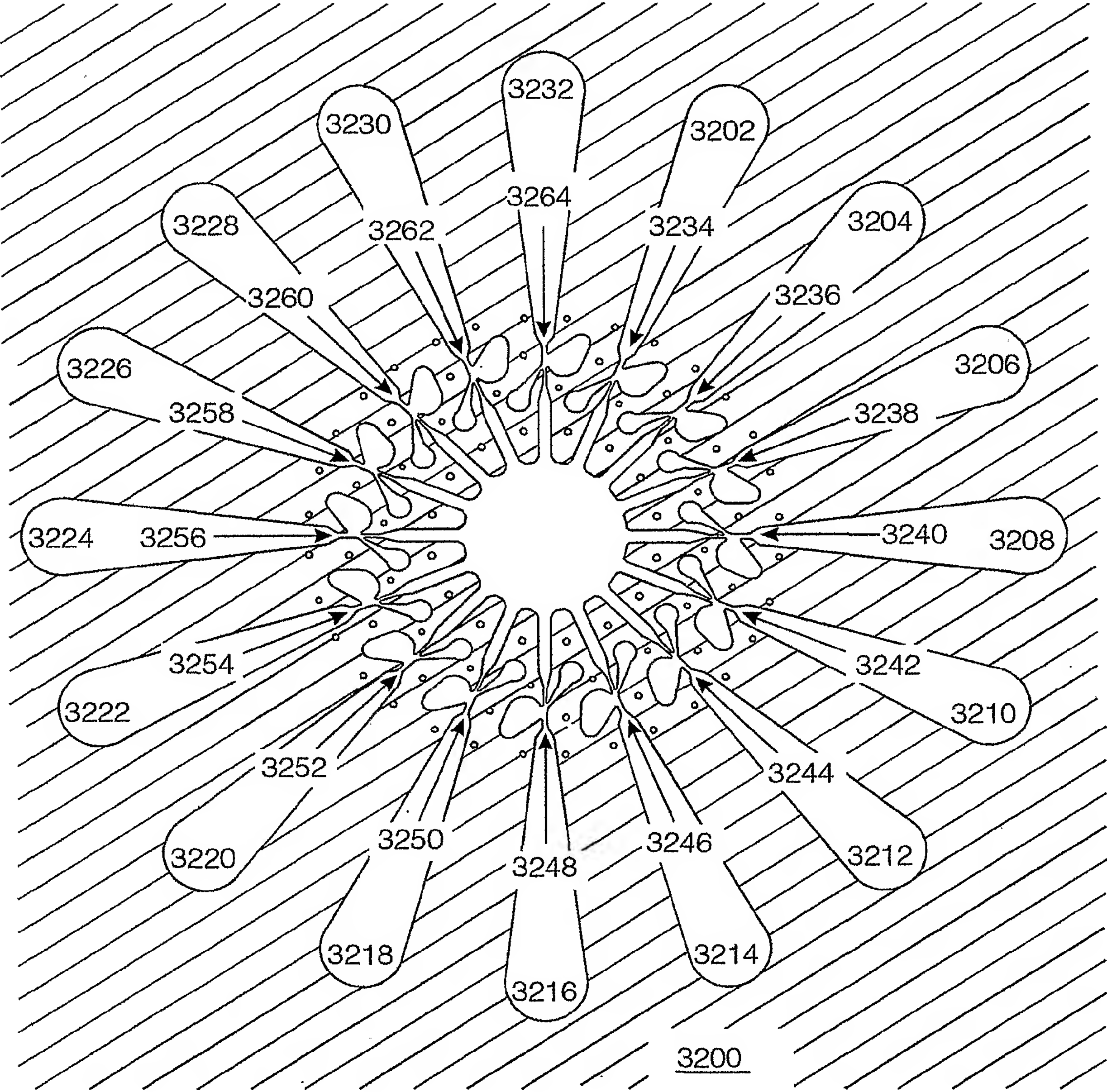


Fig. 32